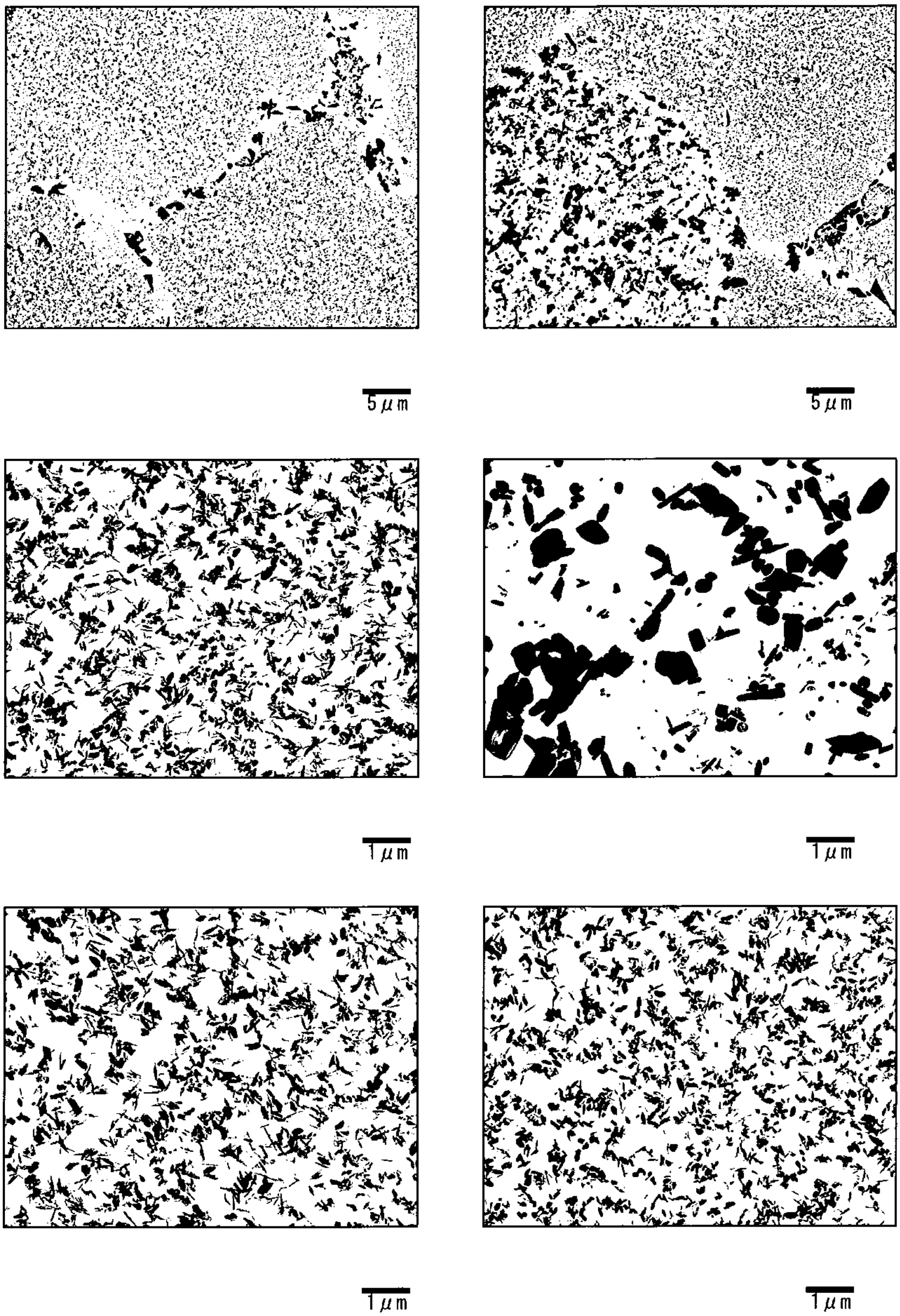


Photo I -8-11 Precipitates by TEM (Transmission electron microscope) observation
RH Outlet Header-Right(Circumferential weld at right side : Base metal)

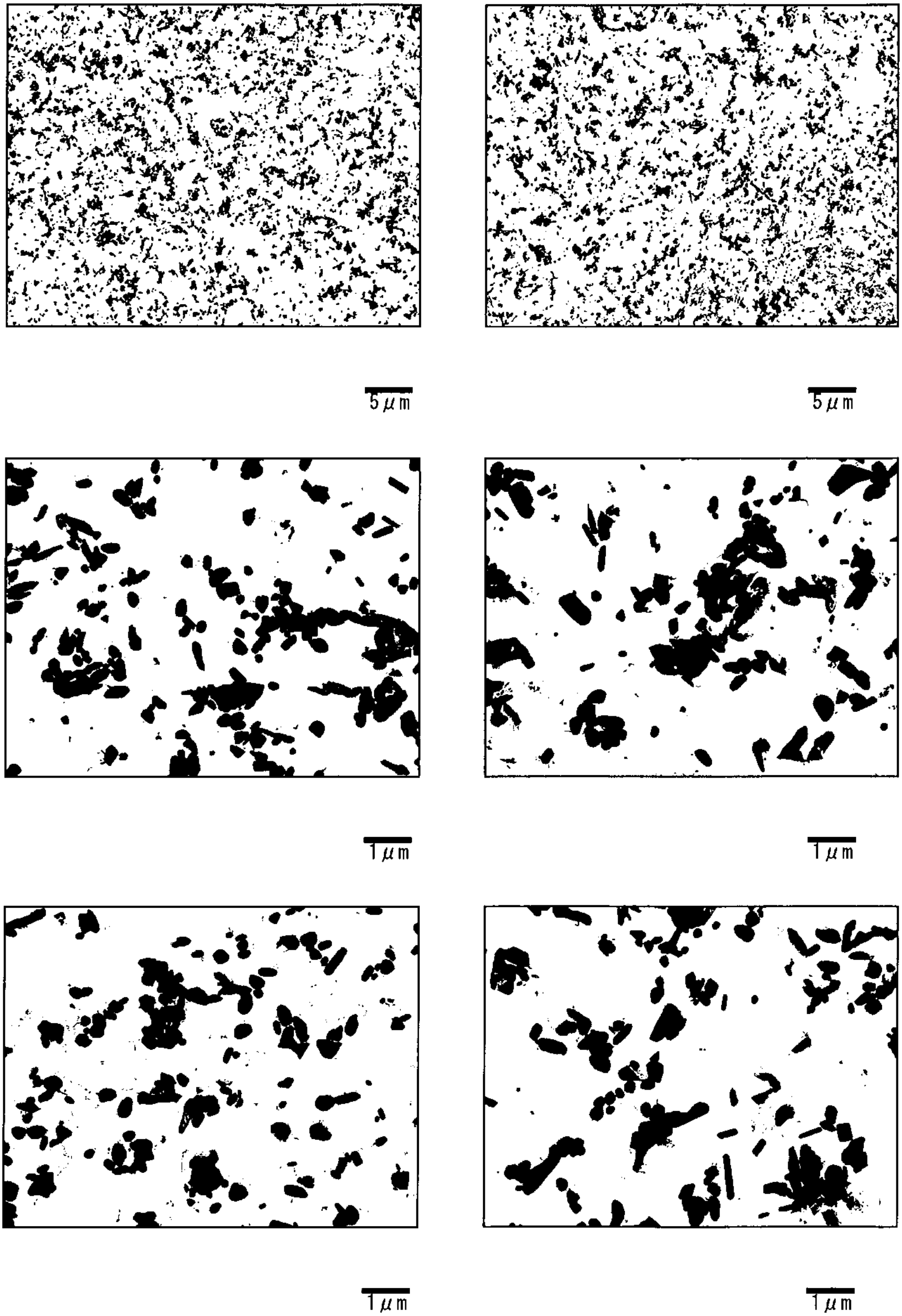


Photo I -8-12 Precipitates by TEM (Transmission electron microscope) observation
RH Outlet Header-Right(Circumferential weld at right side : Fine grain HAZ)

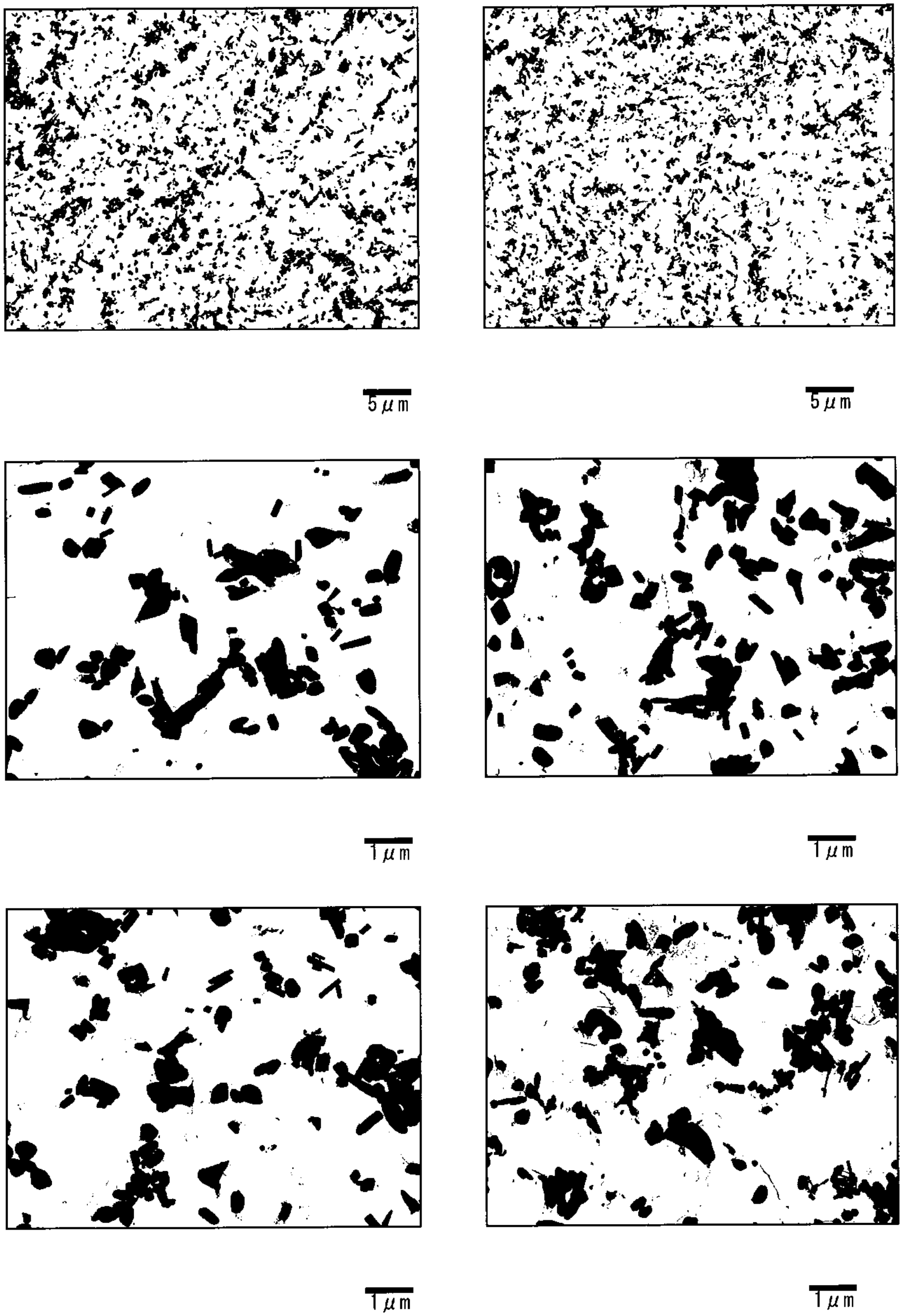


Photo I-8-13 Precipitates by TEM (Transmission electron microscope) observation
RH Outlet Header-Right(Circumferential weld at right side : Coarse grain HAZ)

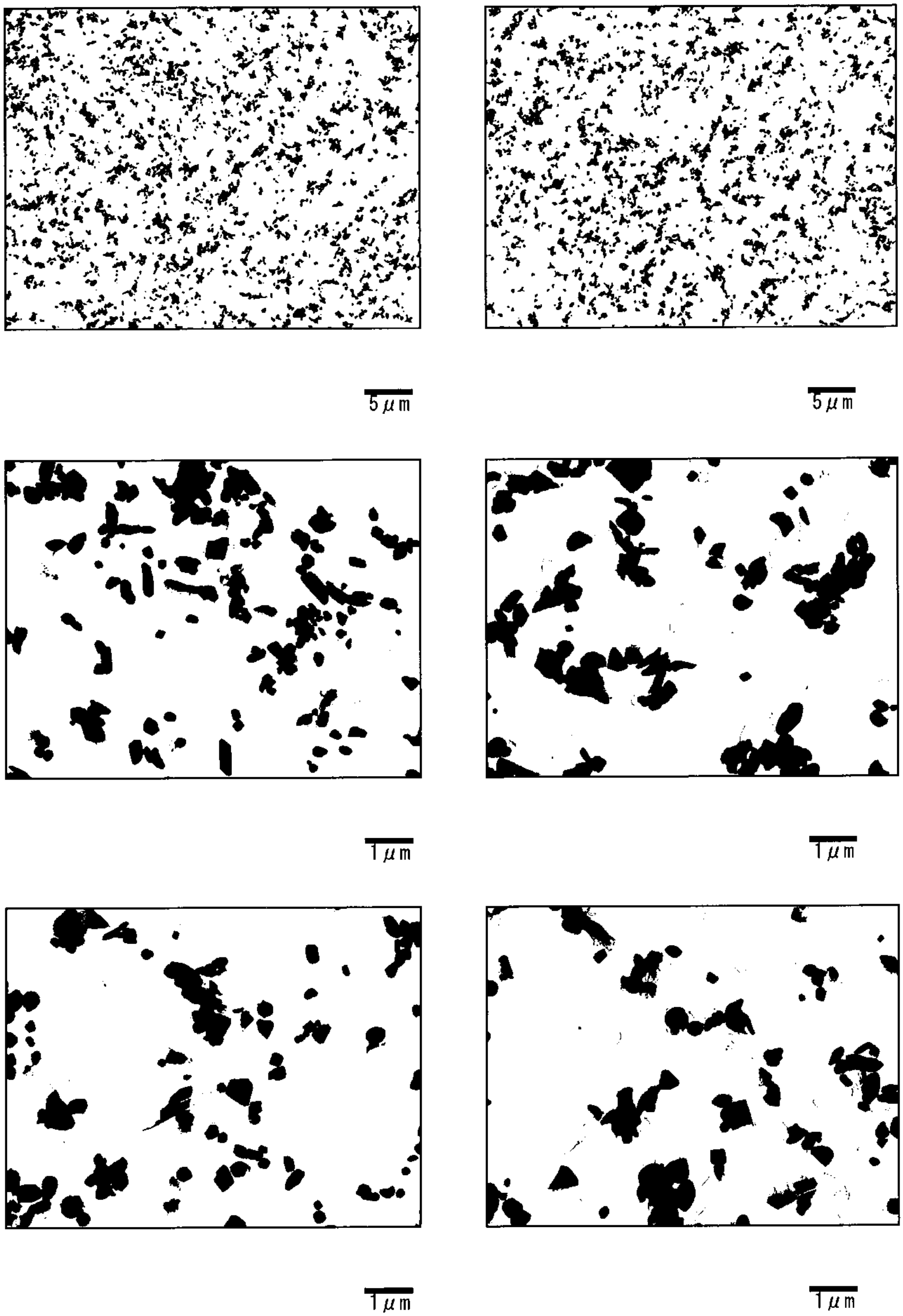


Photo I-8-14 Precipitates by TEM (Transmission electron microscope) observation
RH Outlet Header-Right (Circumferential weld at right side : Weld metal)

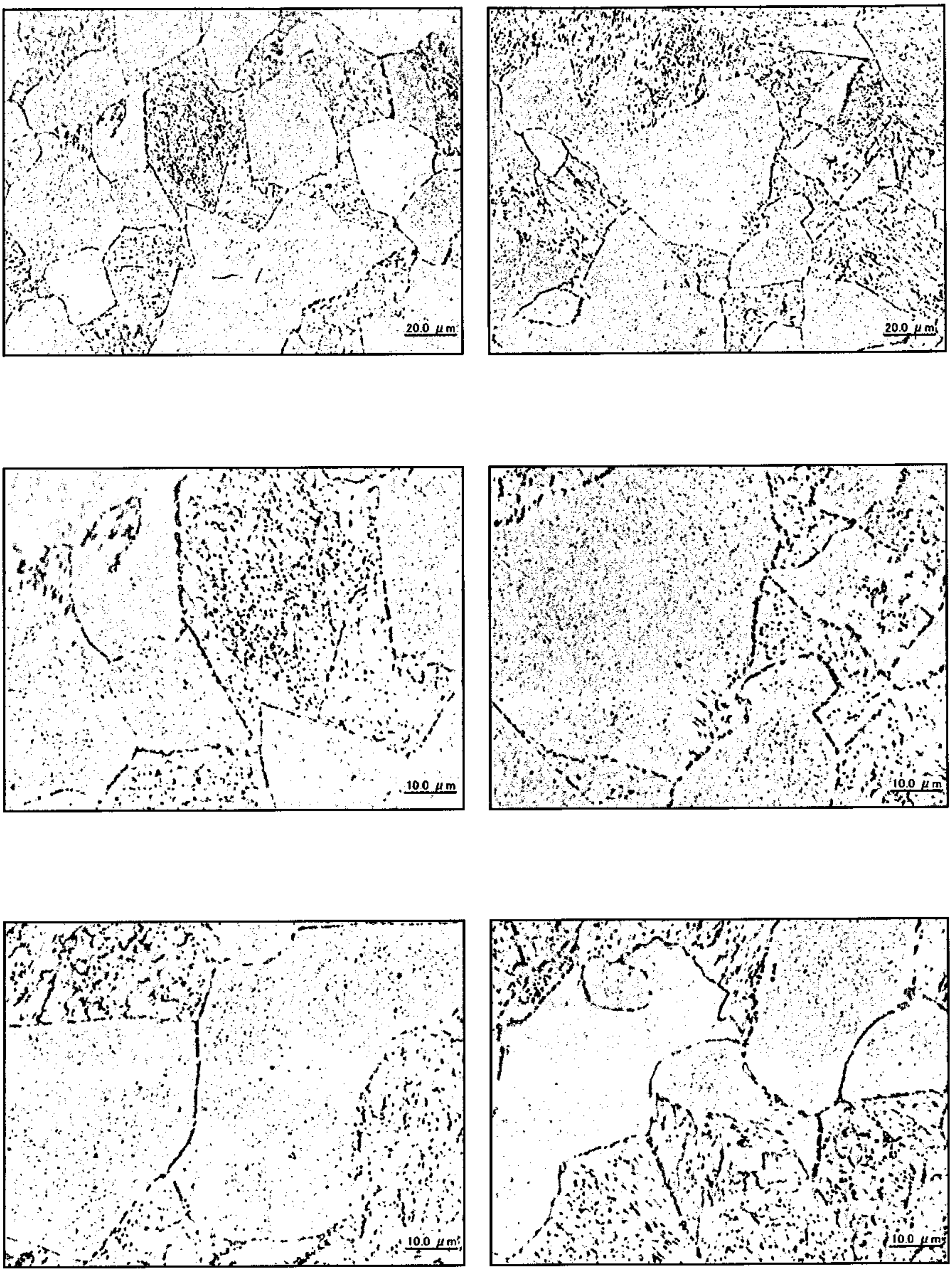


Photo I -9-1 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, extrados : Base metal)

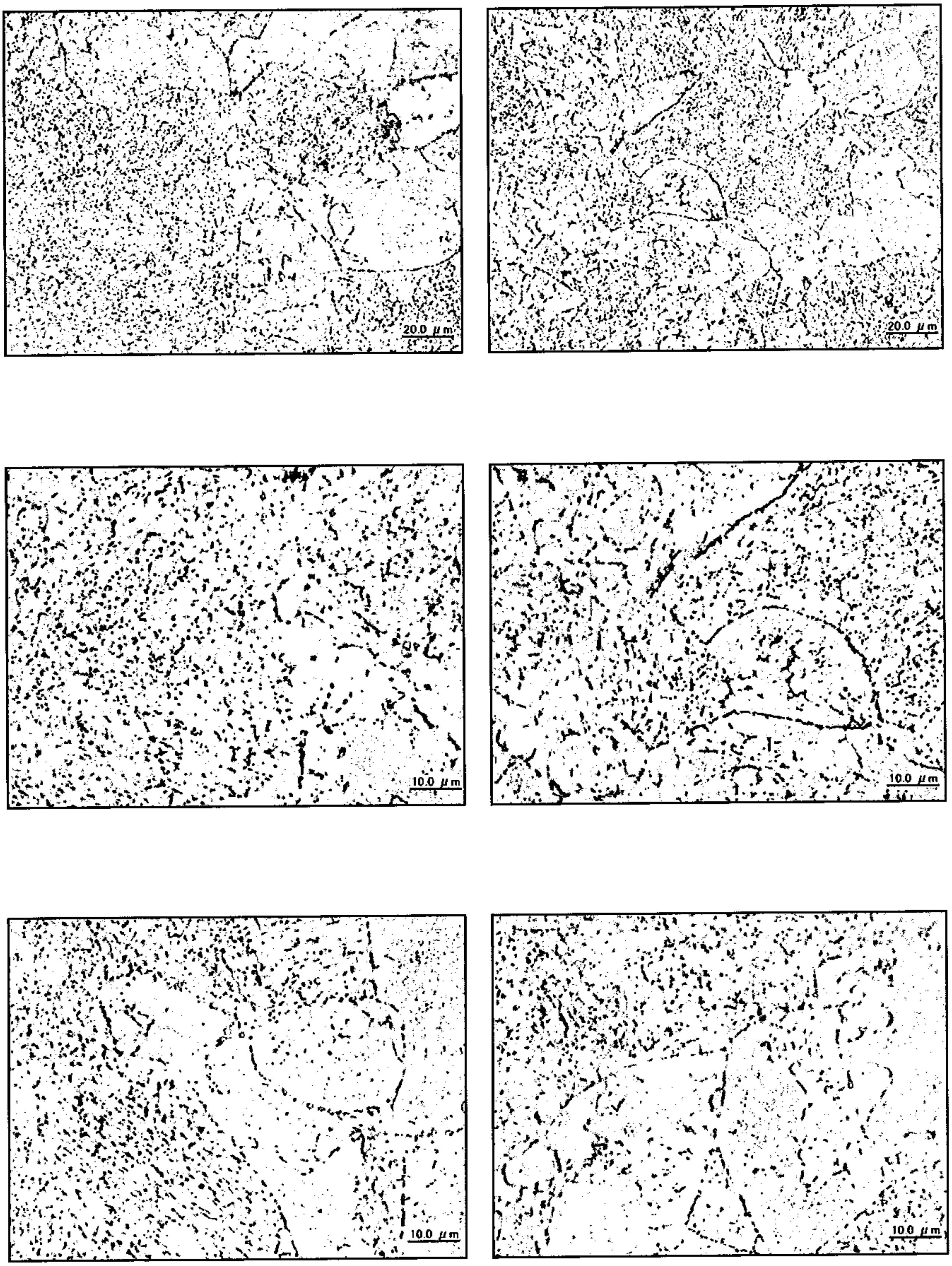


Photo I -9-2 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, extrados : Intercritical zone)

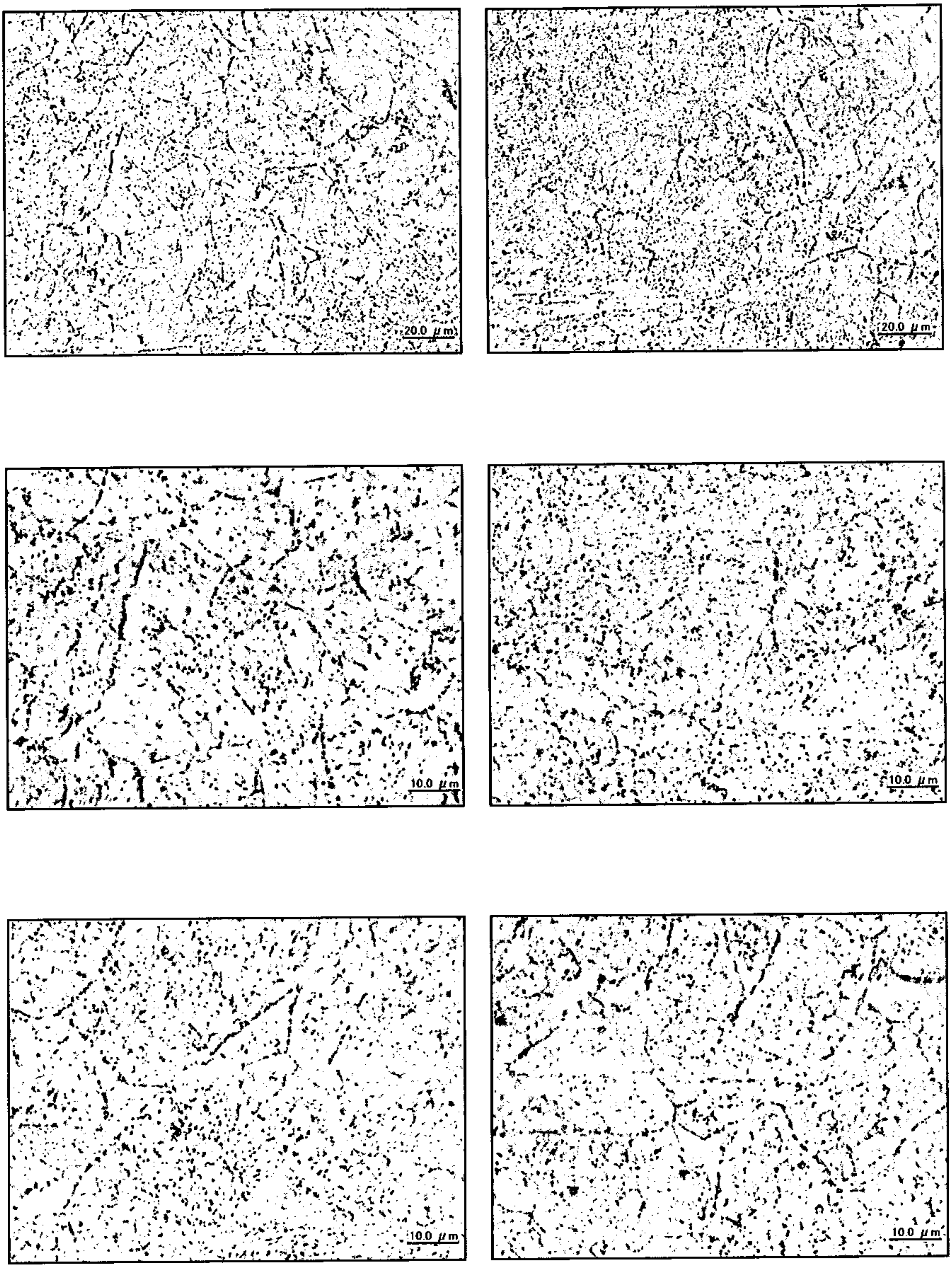


Photo I -9-3 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, extrados : Fine grain HAZ)

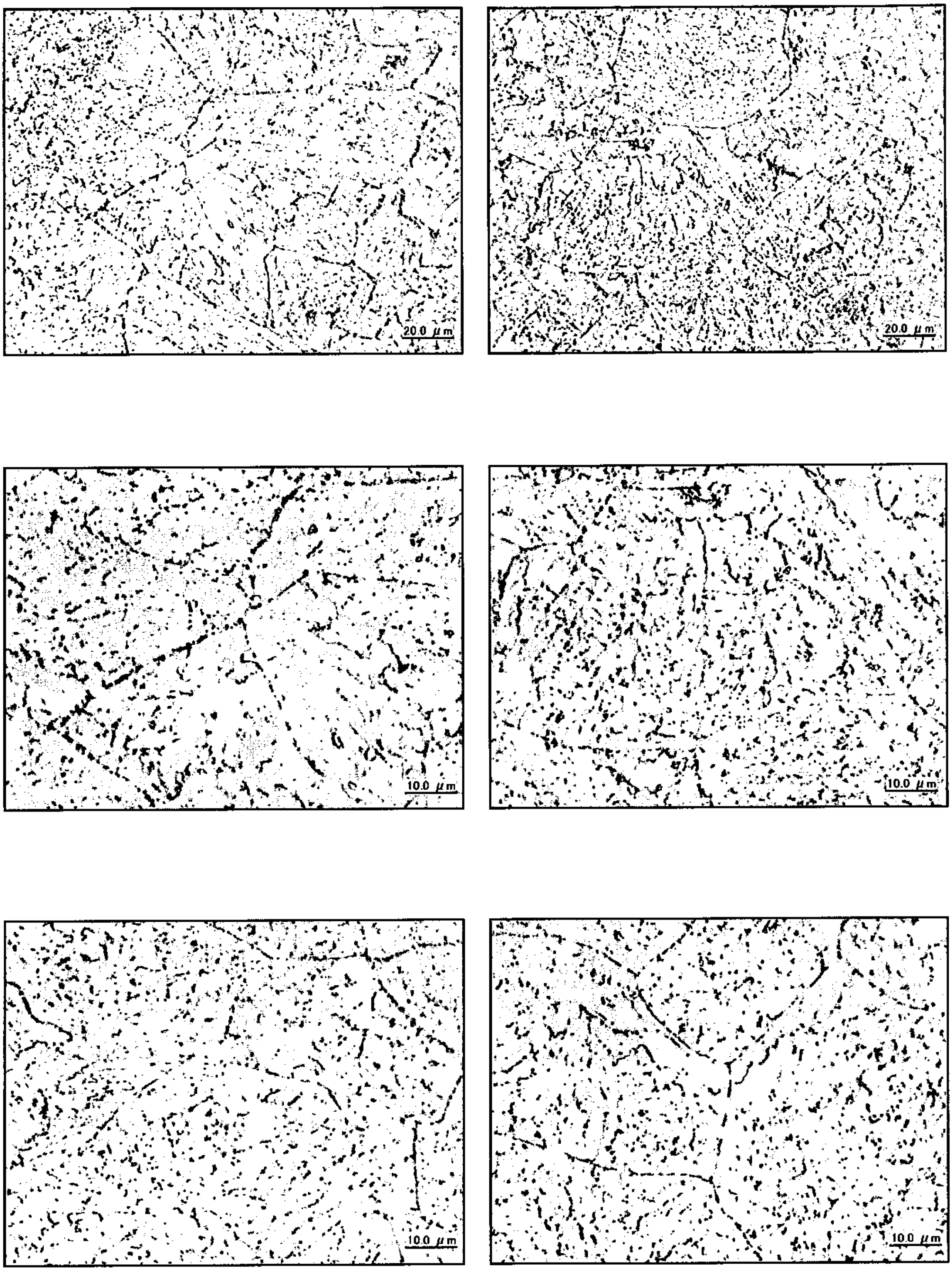


Photo I -9-4 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, extrados : Coarse grain HAZ)

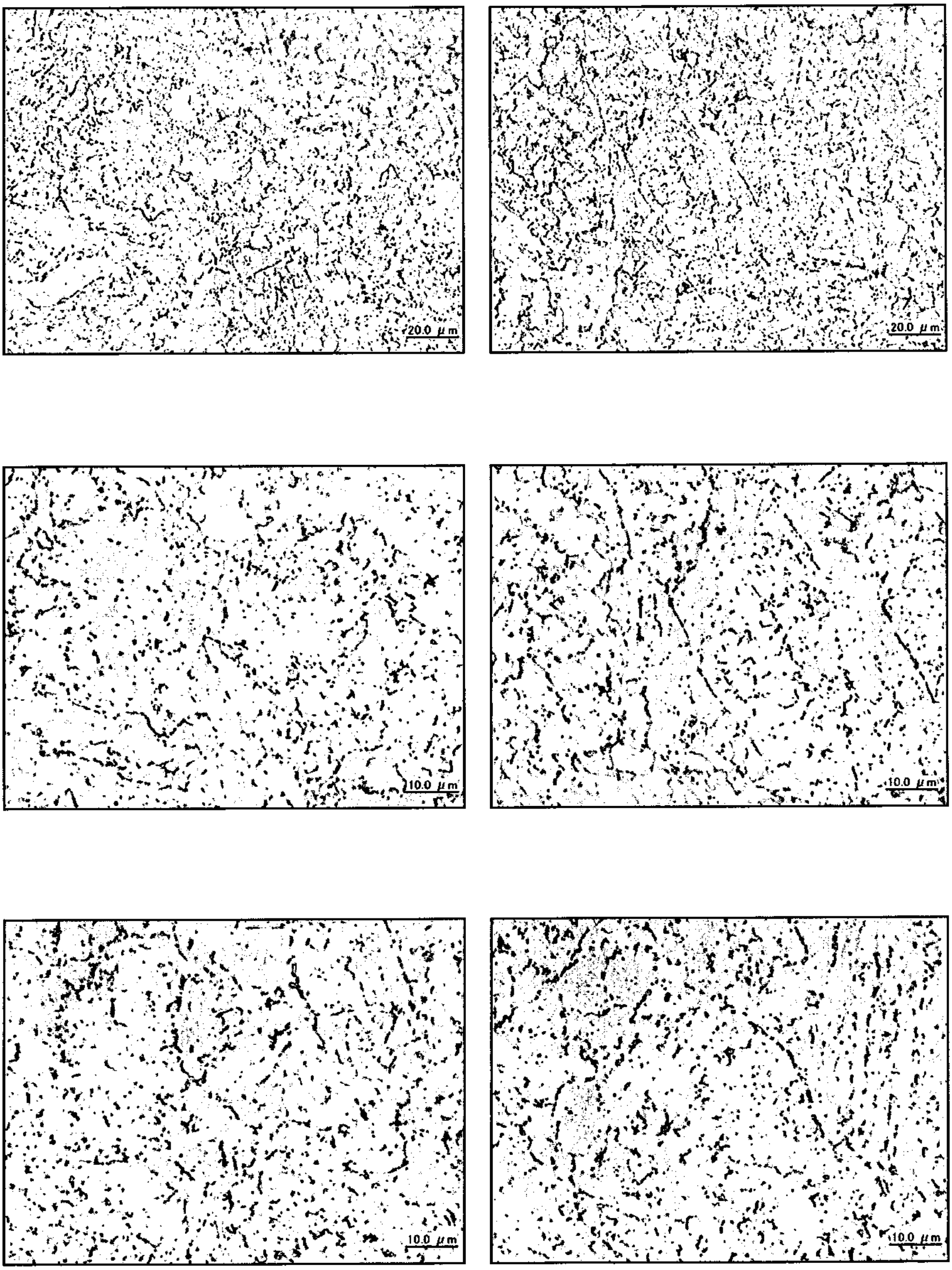


Photo I -9-5 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, extrados : Weld metal)

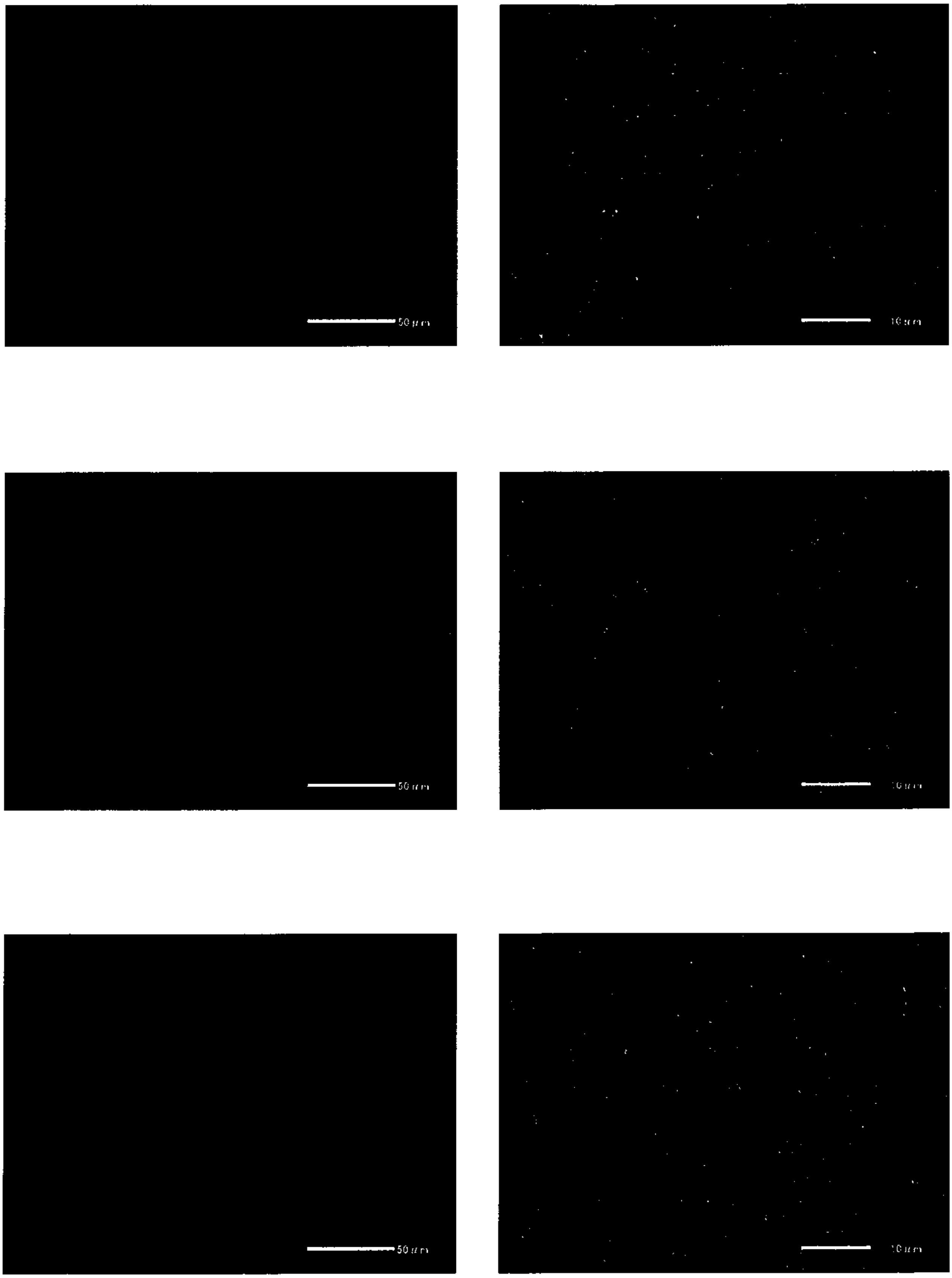


Photo I -9-6 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Fine grain HAZ)

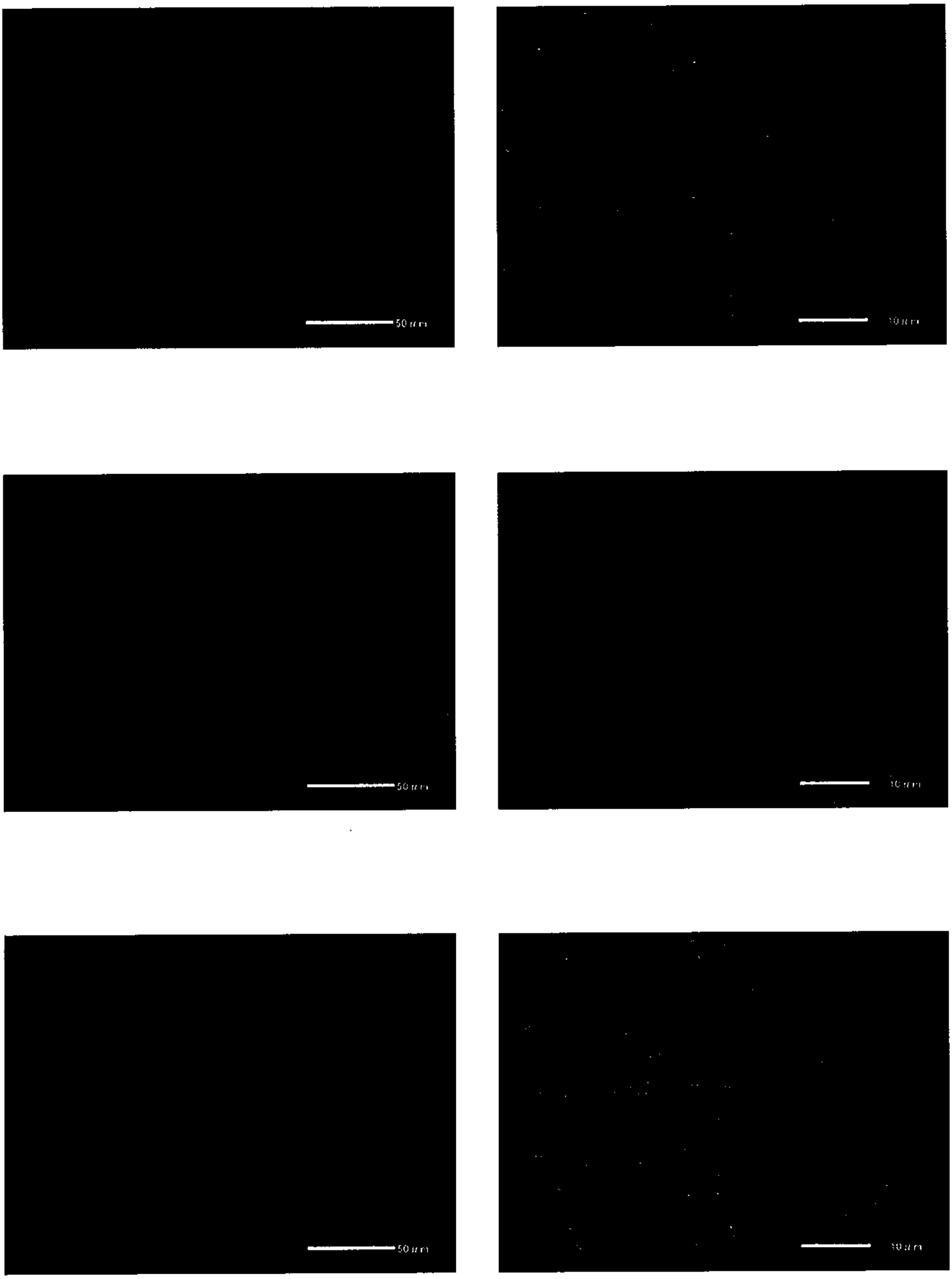


Photo I -9-7 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Coarse grain HAZ)

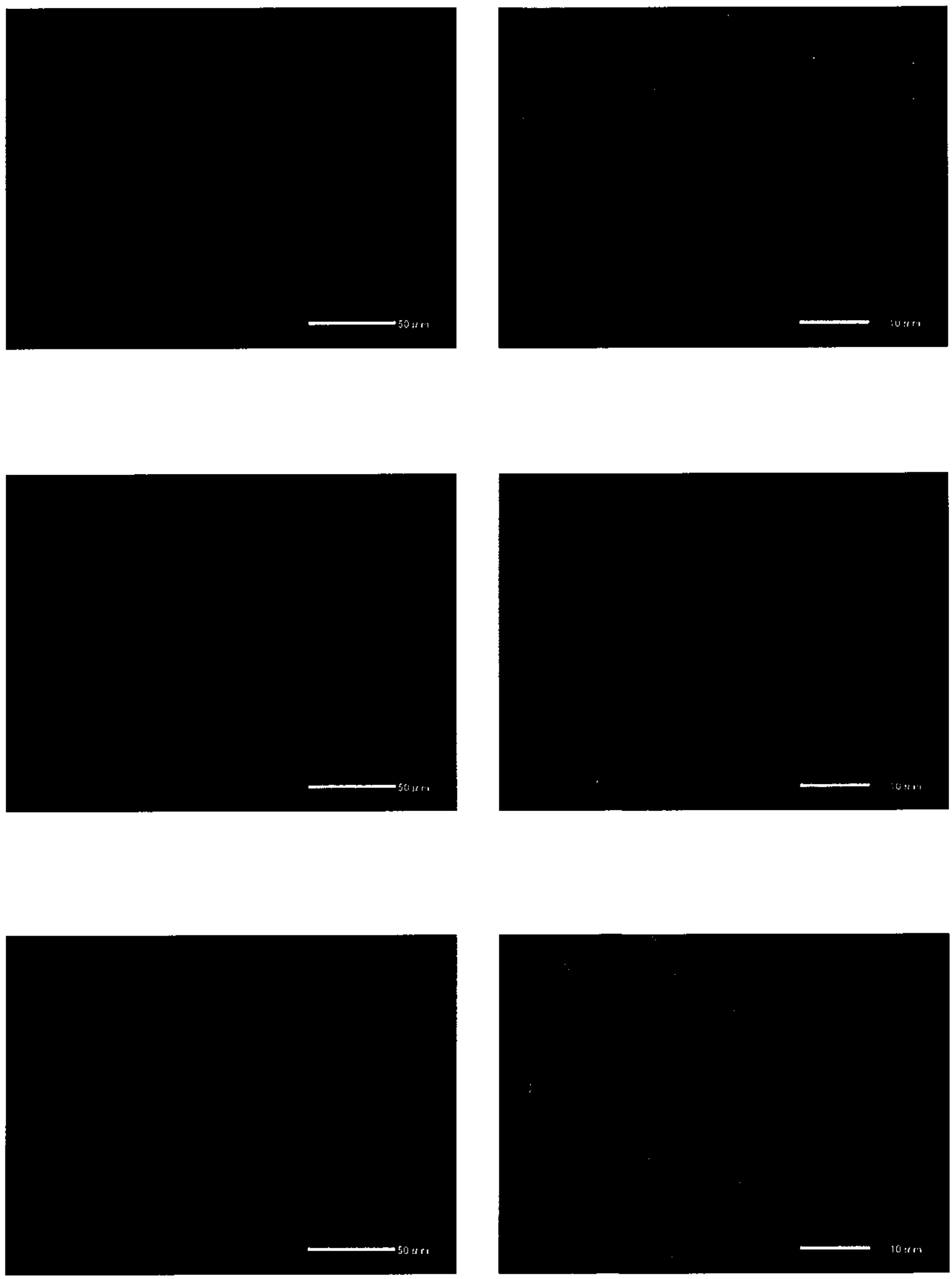


Photo I -9-8 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Weld metal)

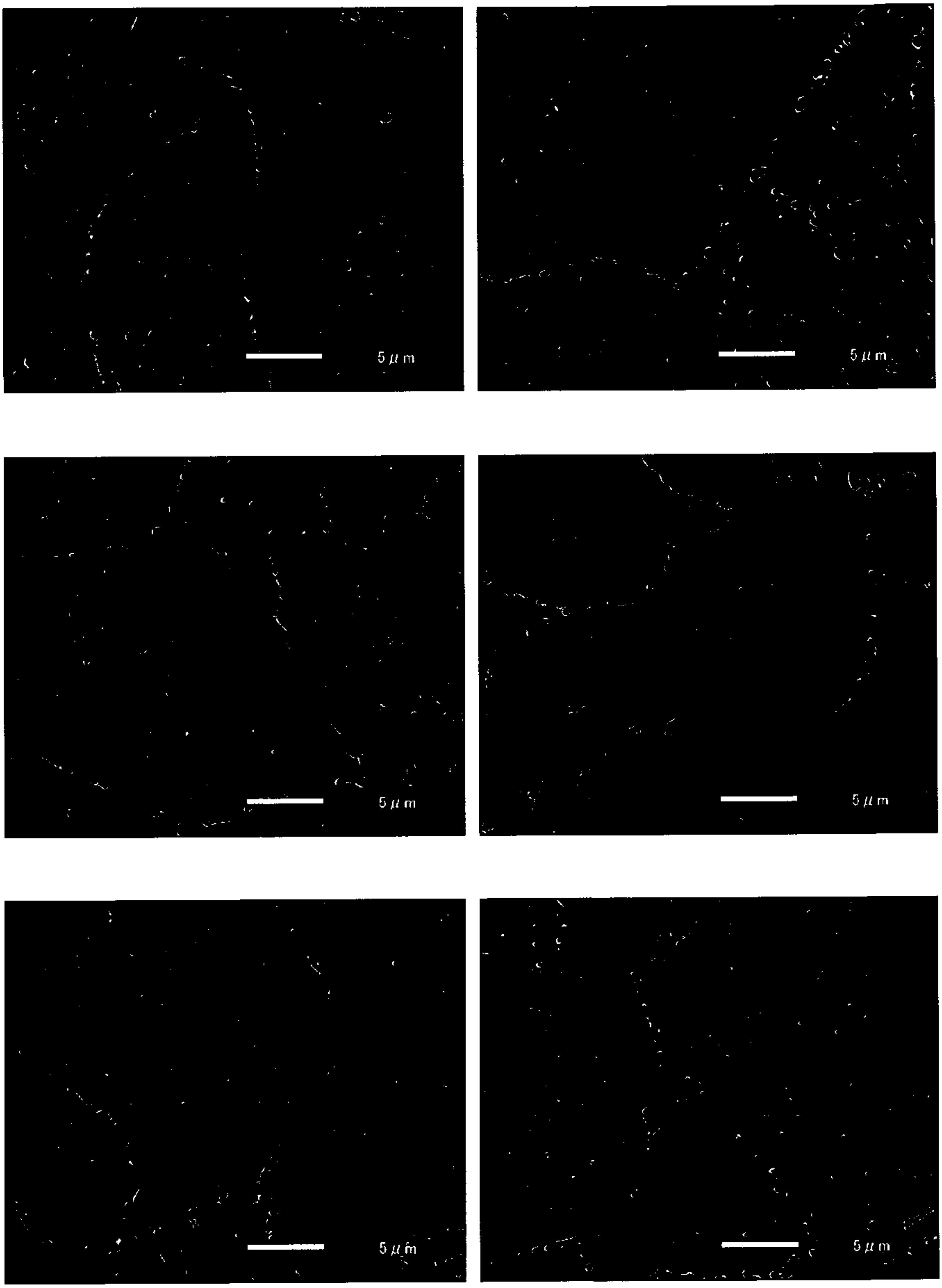


Photo I-9-9 Precipitates along grain boundary by SEM observation
Main Steam Pipe-Left (Circumferential weld, extrados : Base metal)

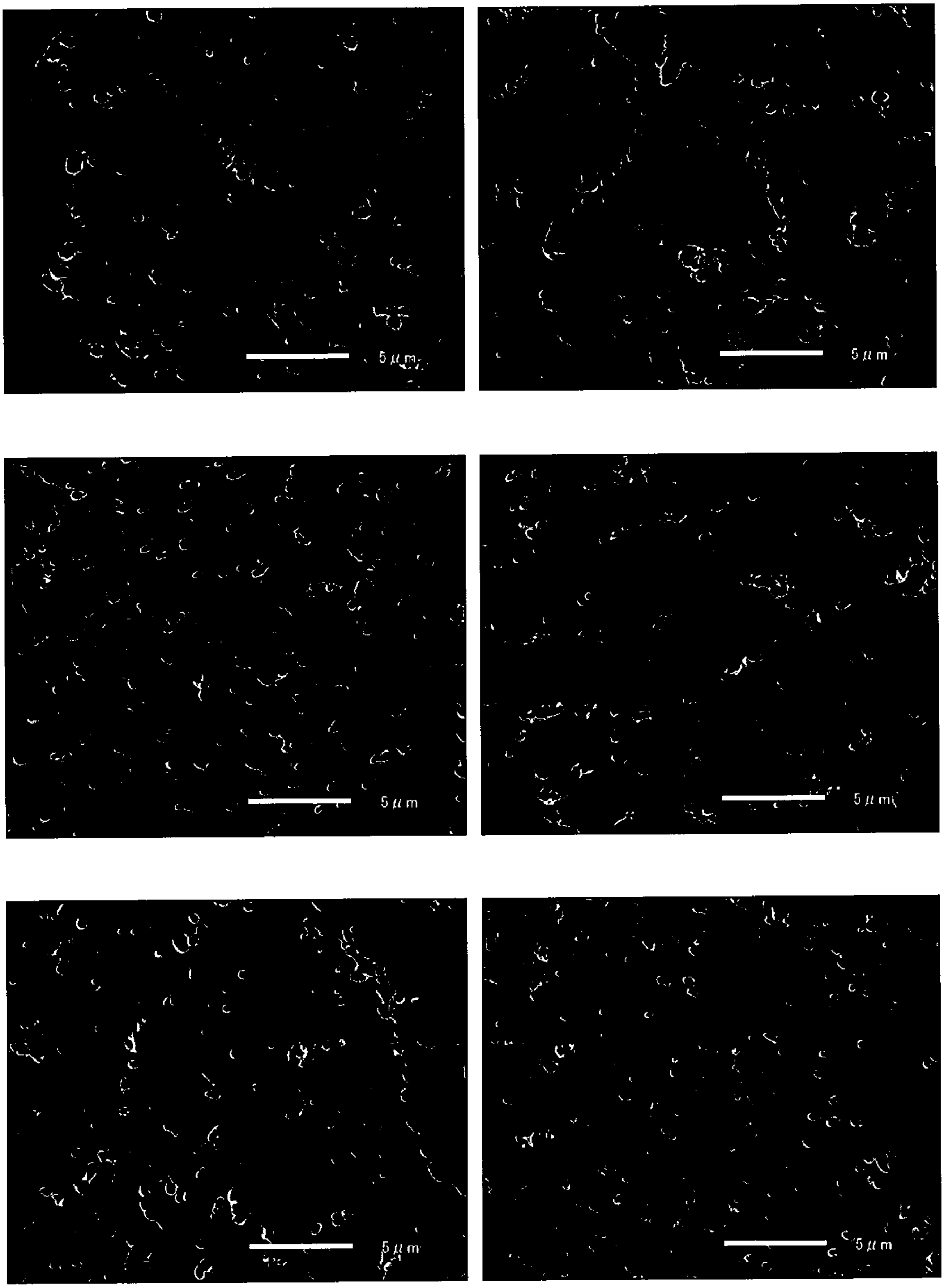


Photo I -9-10 Precipitates along grain boundary by SEM observation
Main Steam Pipe-Left (Circumferential weld, extrados : Fine grain HAZ)

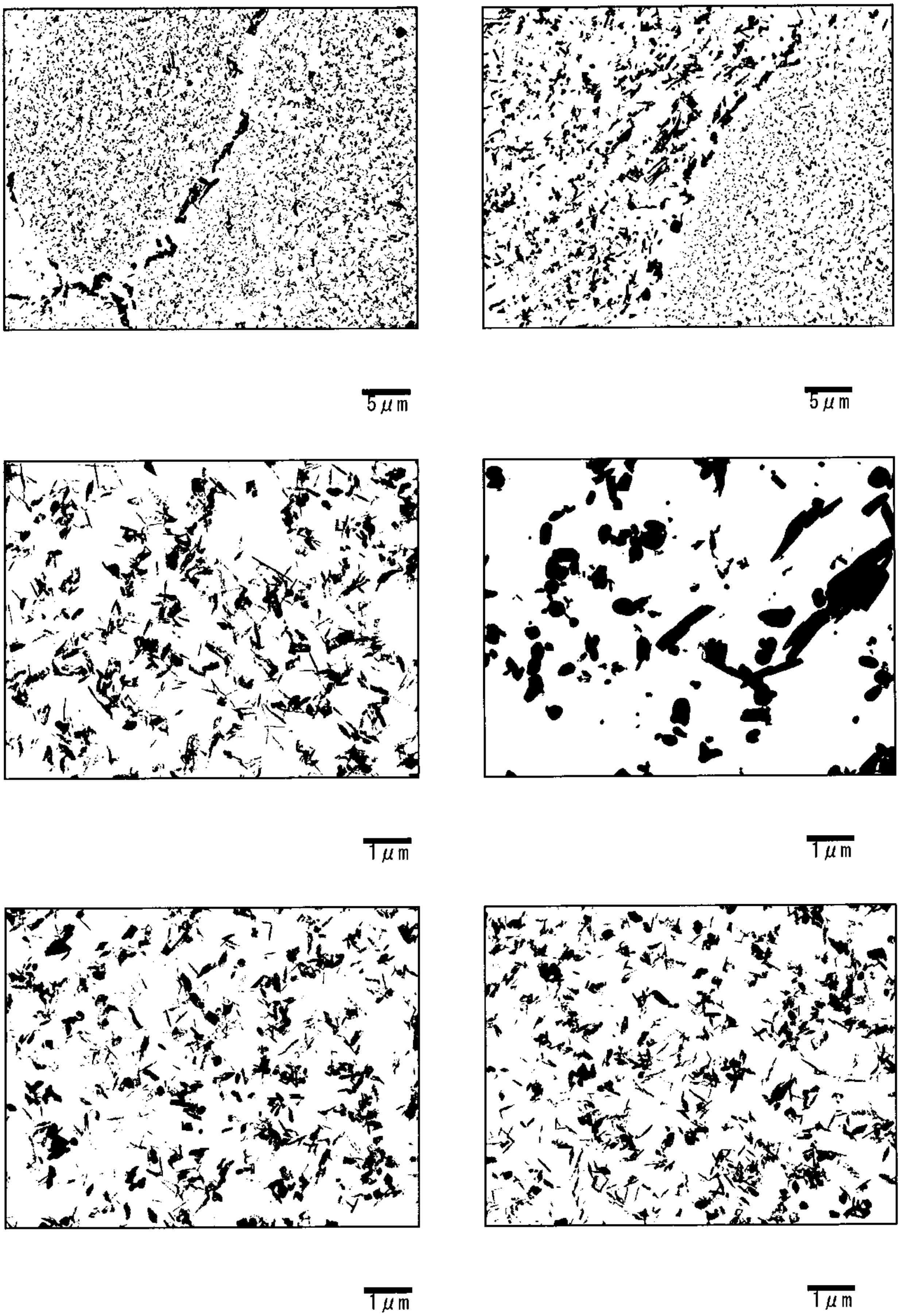


Photo I -9-11 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Base metal)

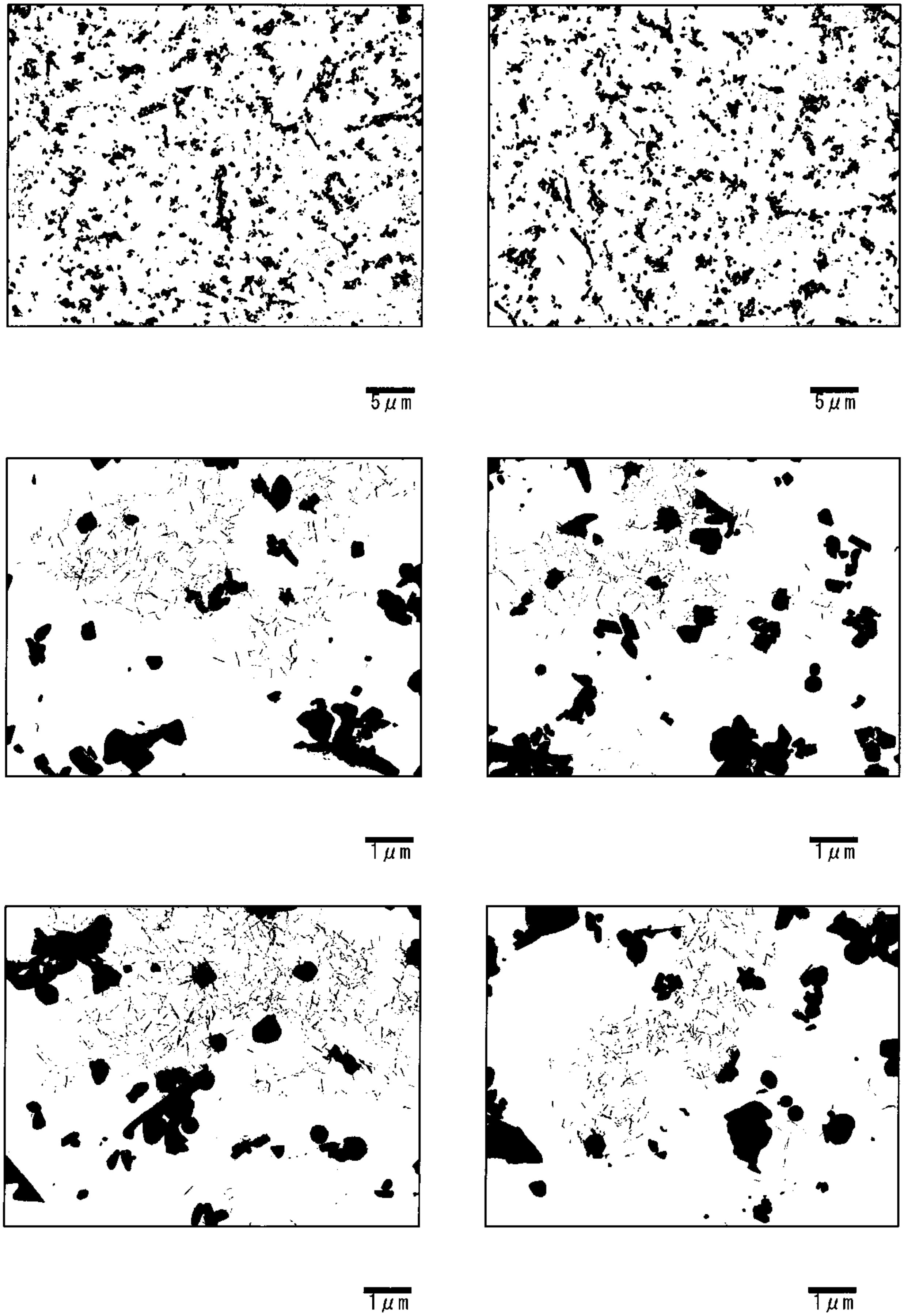


Photo I -9-12 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Fine grain HAZ)

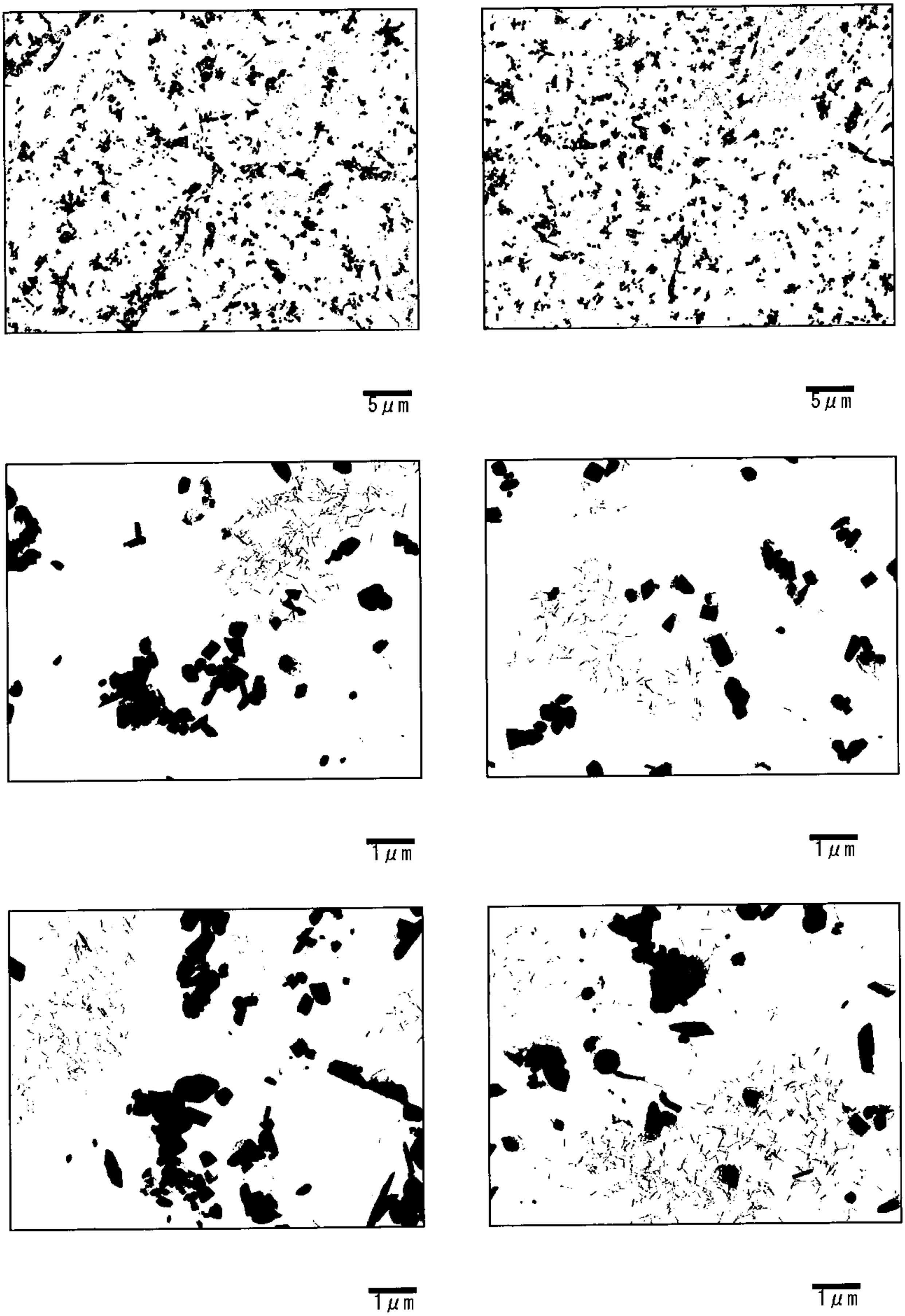


Photo I -9-13 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left (Circumferential weld, extrados : Coarse grain HAZ)

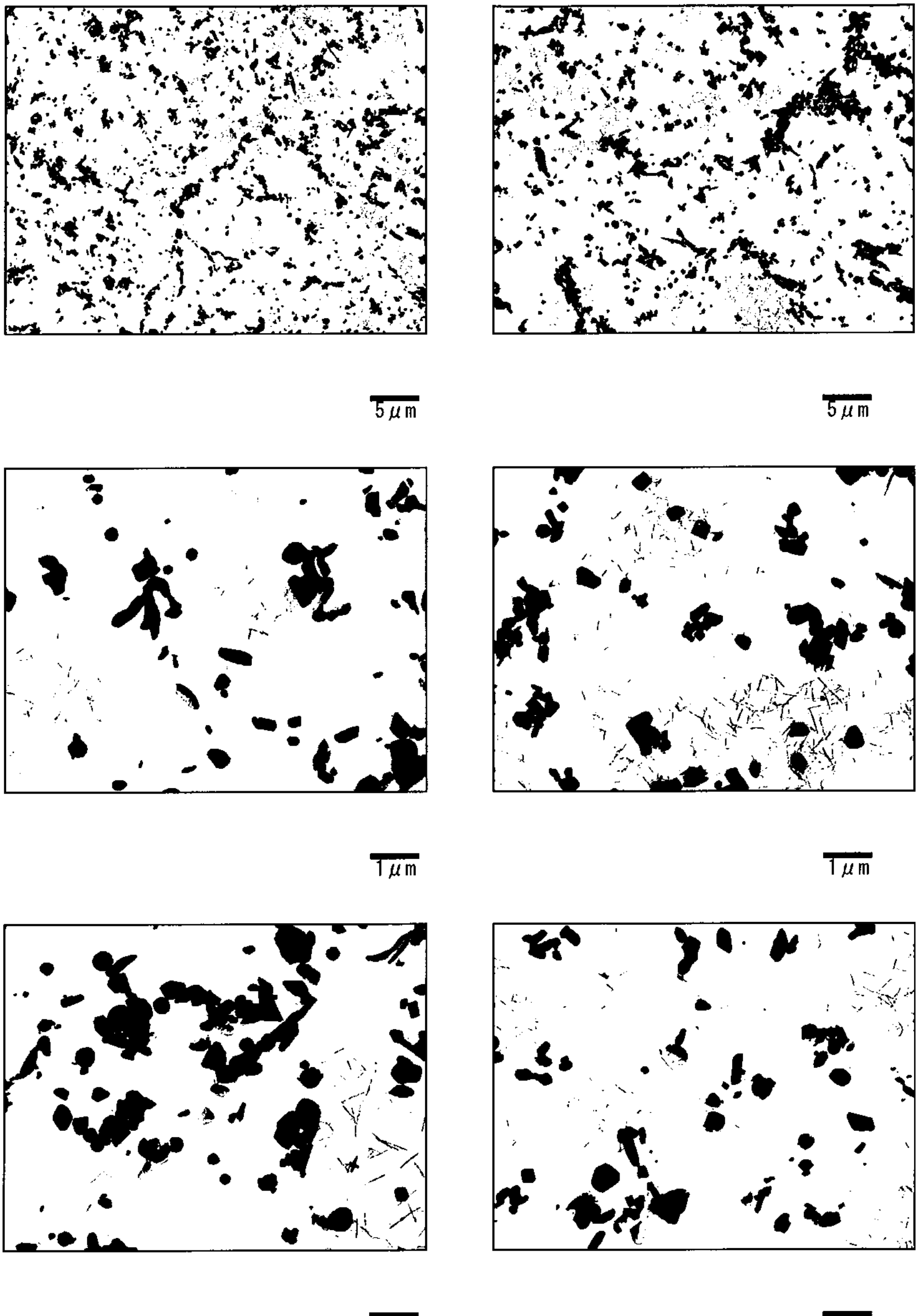


Photo I -9-14 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, extrados : Weld metal)

Photo I -10-1 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, intrados : Base metal)

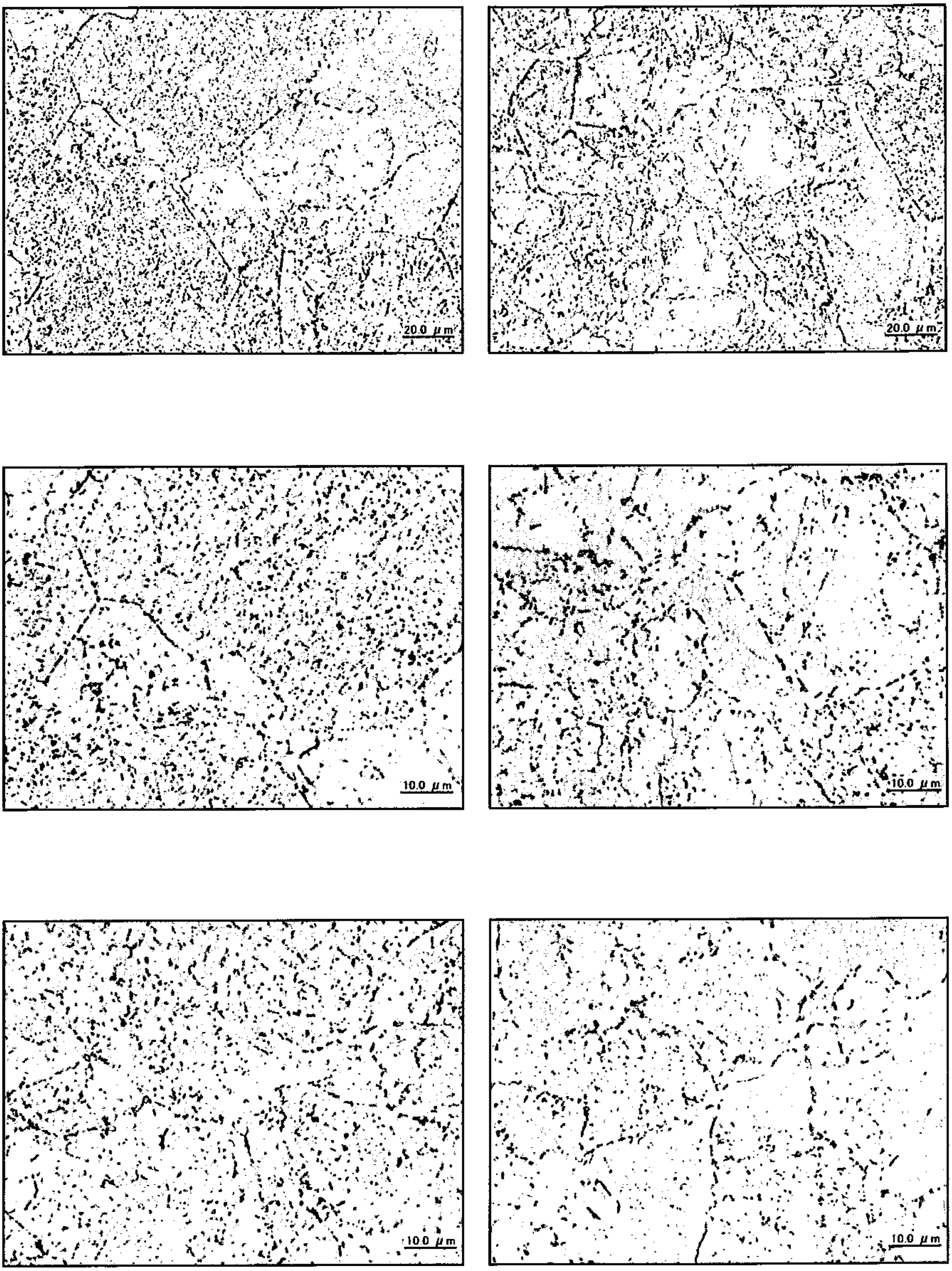


Photo I -10-2 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, intrados : Intercritical zone)

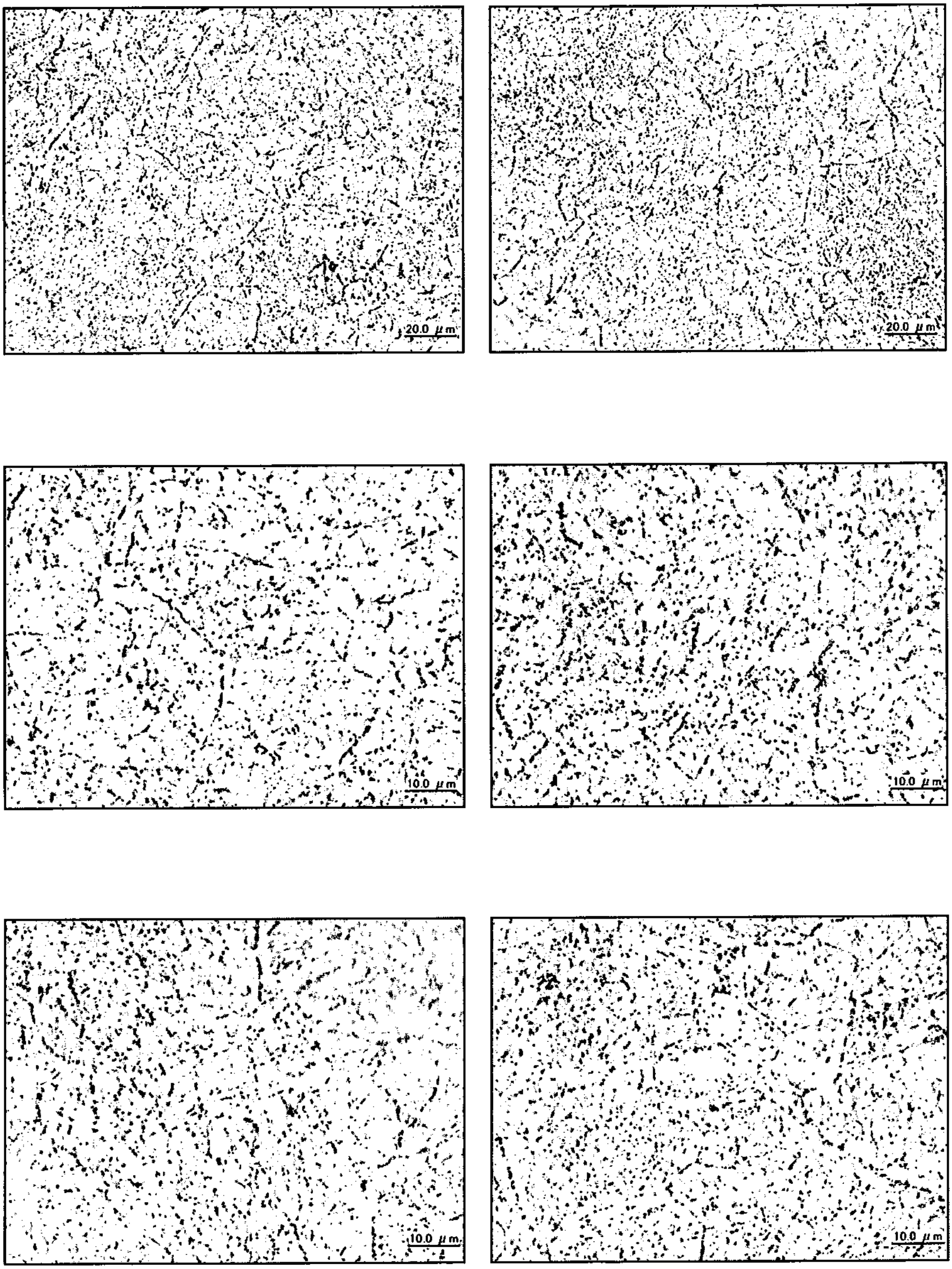


Photo I -10-3 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, intrados : Fine grain HAZ)

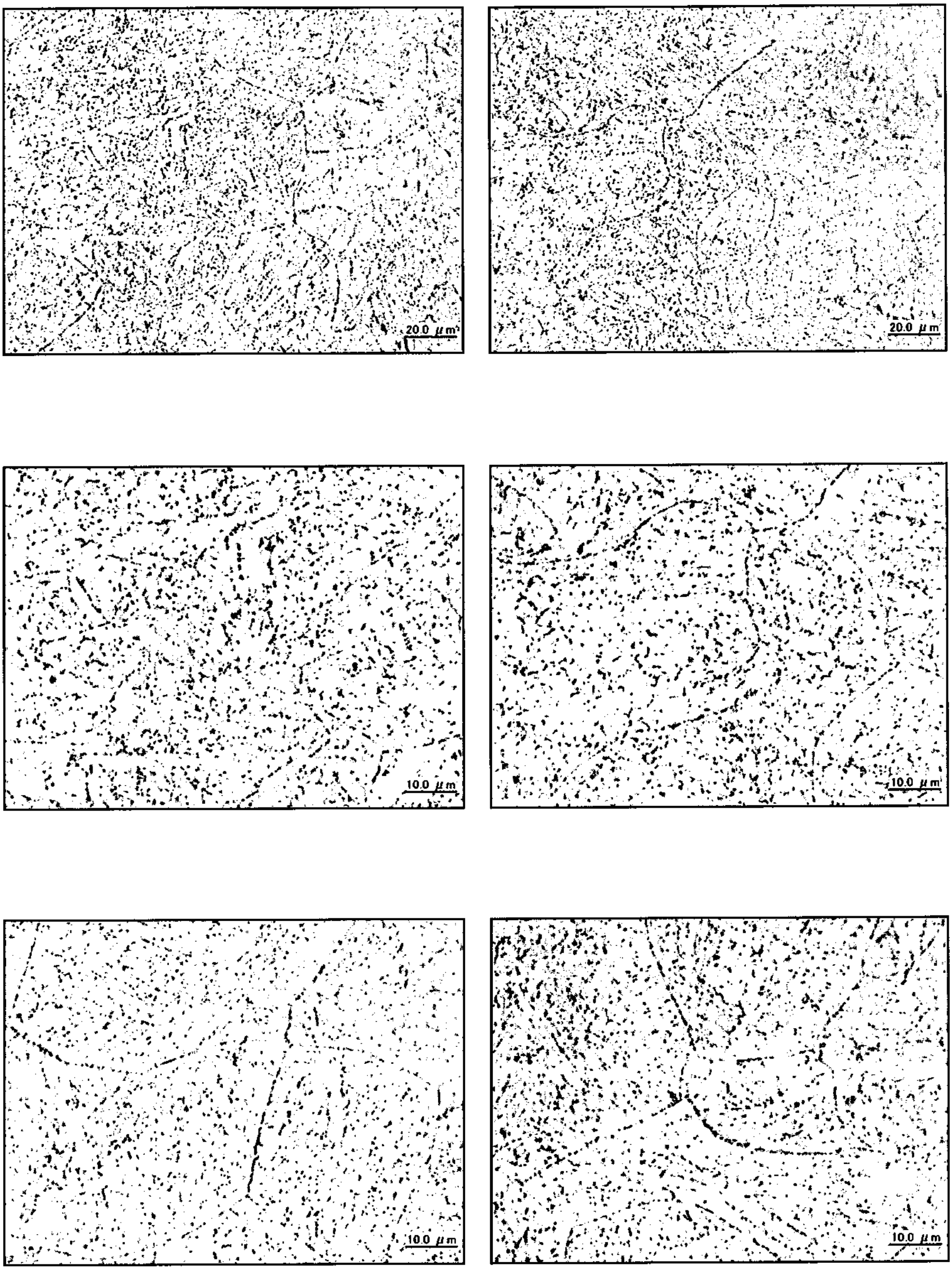


Photo I -10-4 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, intrados : Coarse grain HAZ)

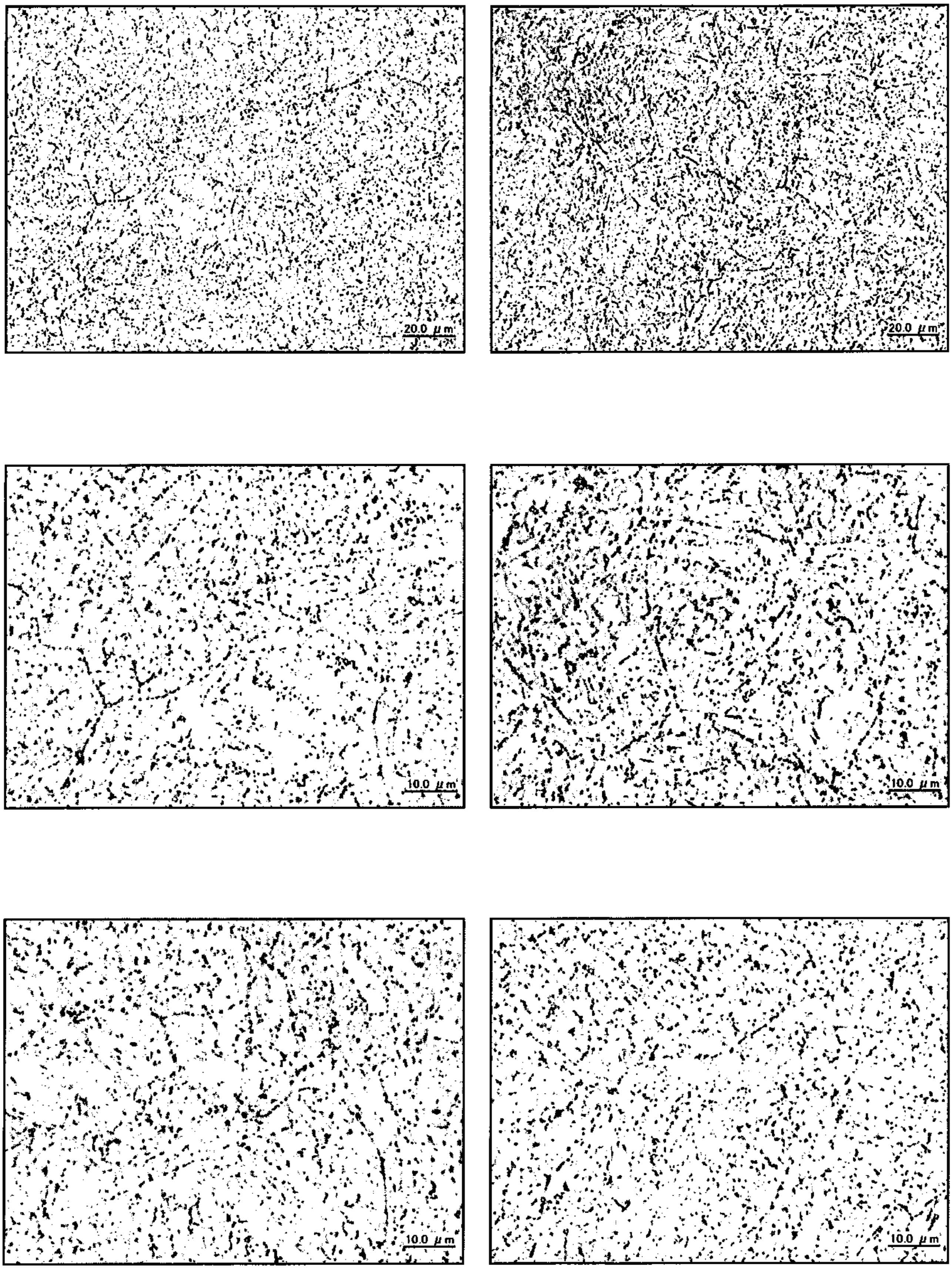


Photo I -10-5 Microstructure observation
Main Steam Pipe-Left (Circumferential weld, intrados : Weld metal)

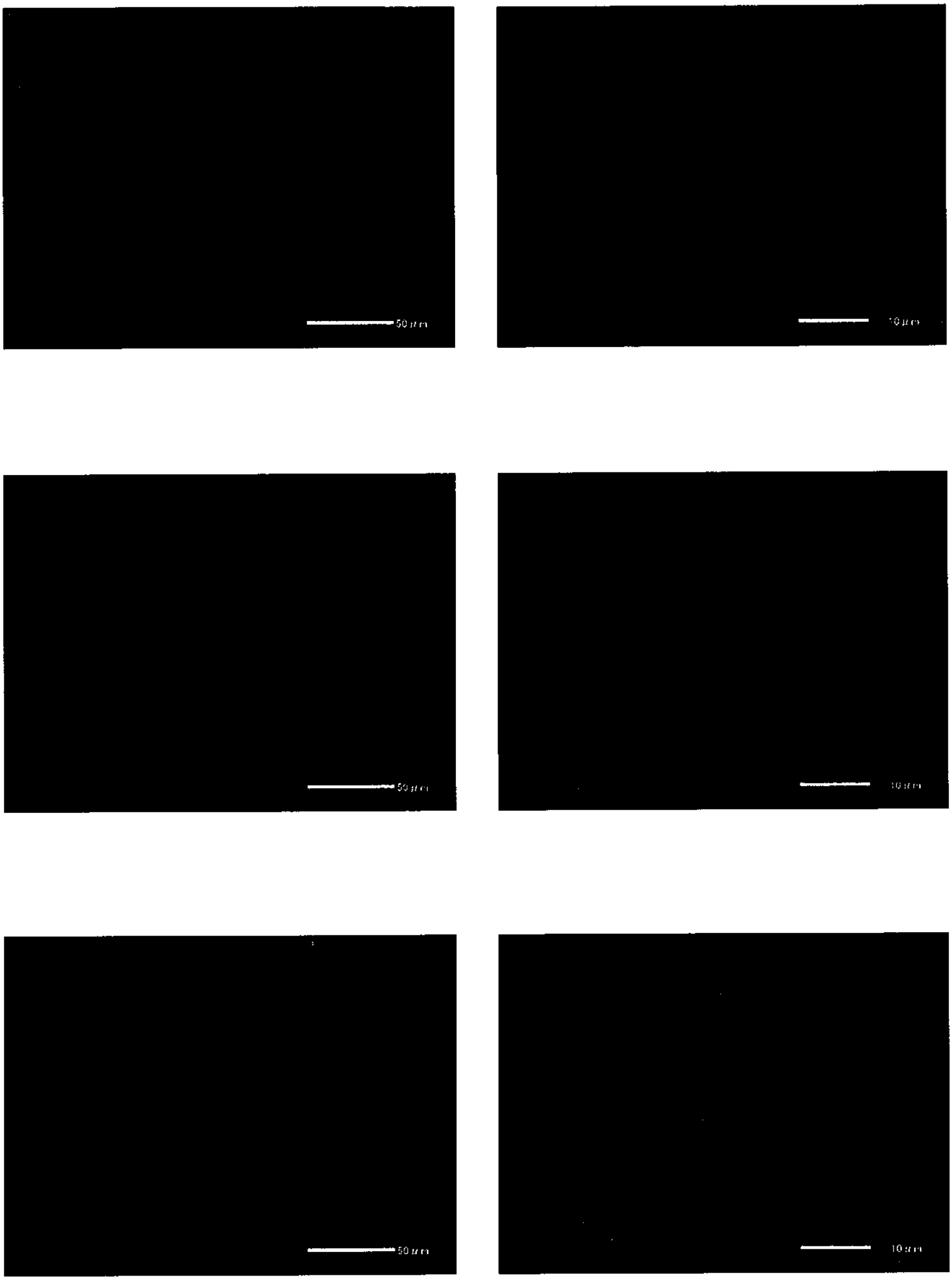


Photo I -10-6 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, intrados : Fine grain HAZ)

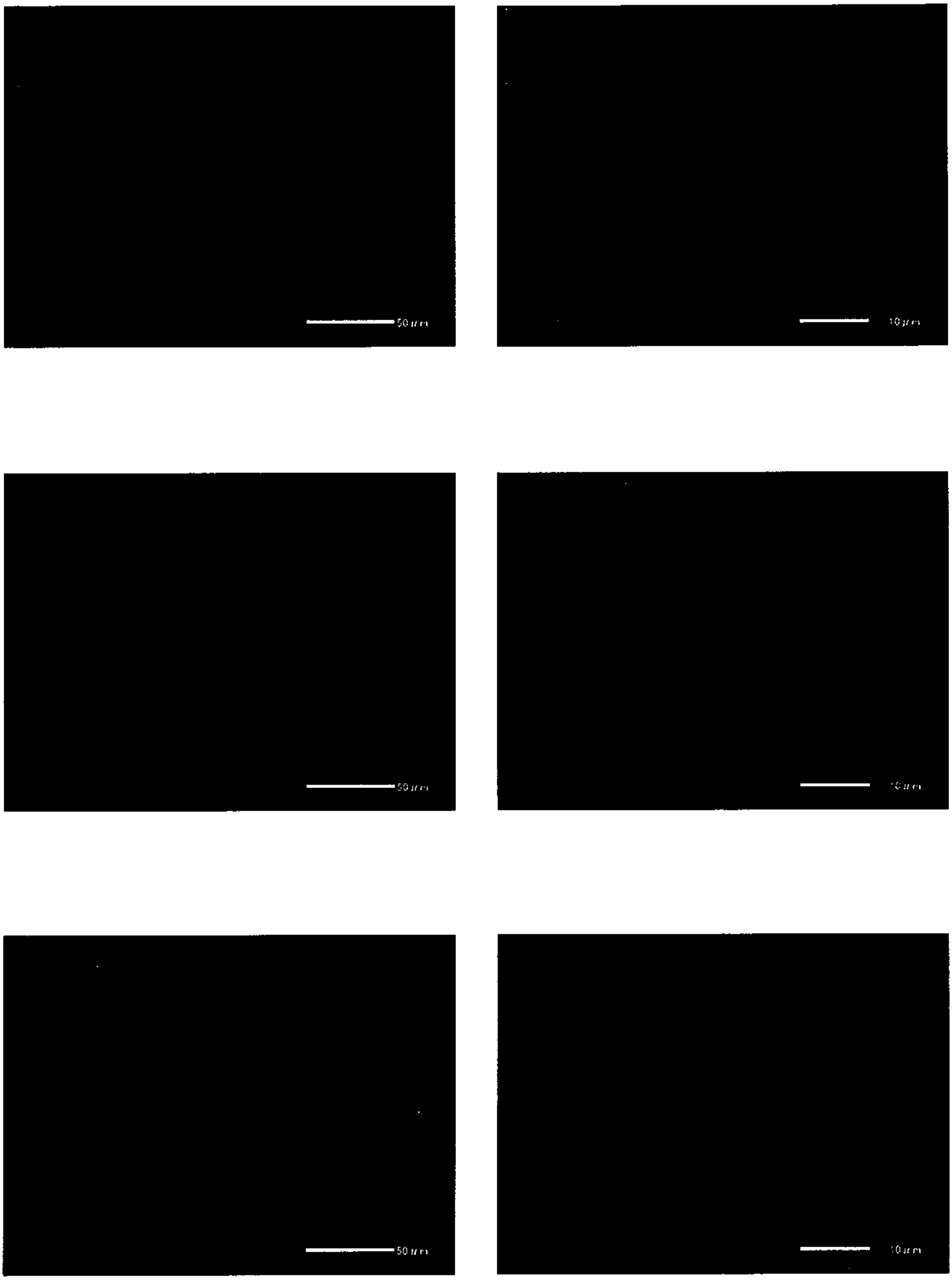


Photo I-10-7 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, intrados : Coarse grain HAZ)

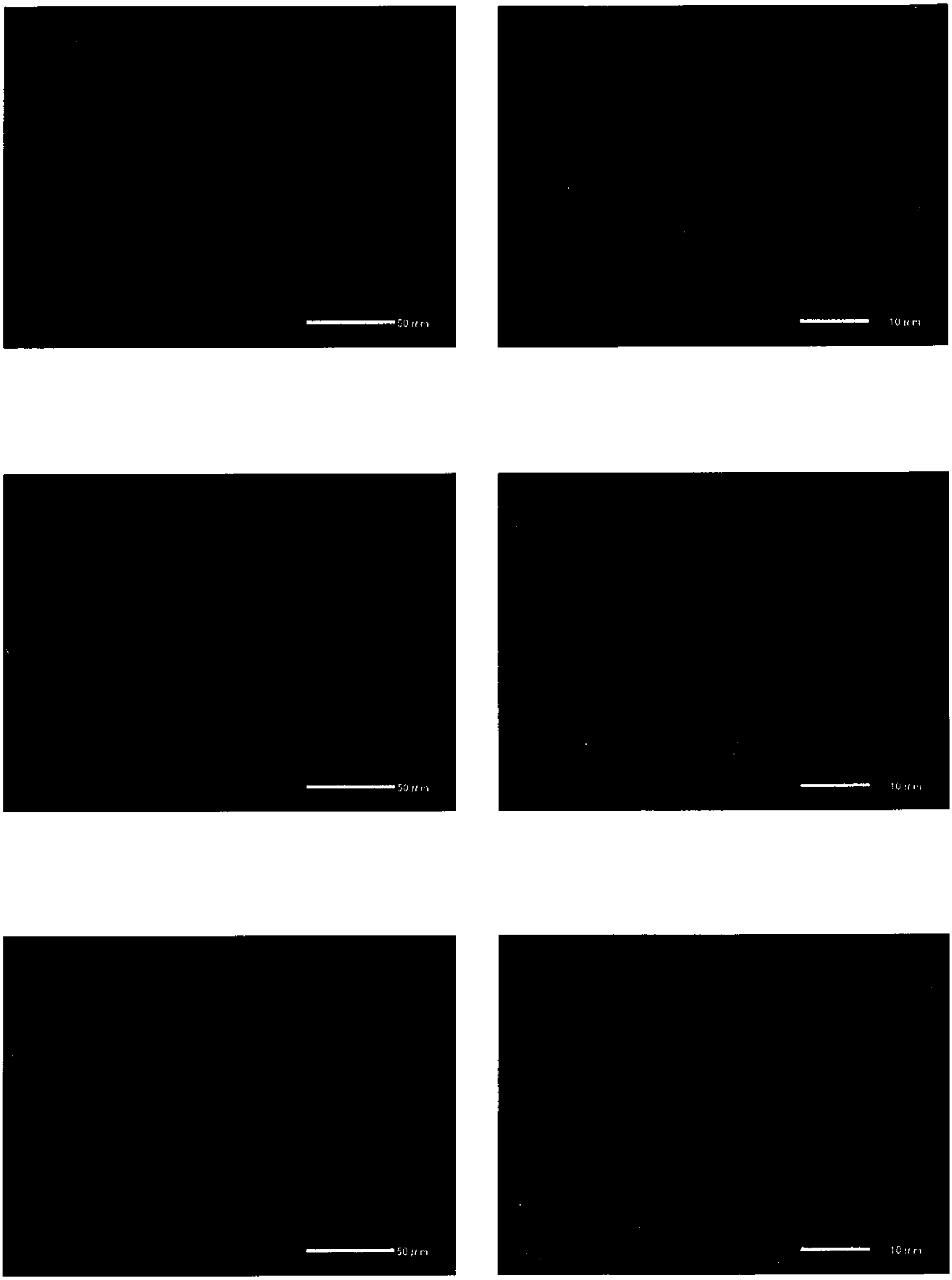


Photo I -10-8 SEM(Scanning electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, intrados : Weld metal)

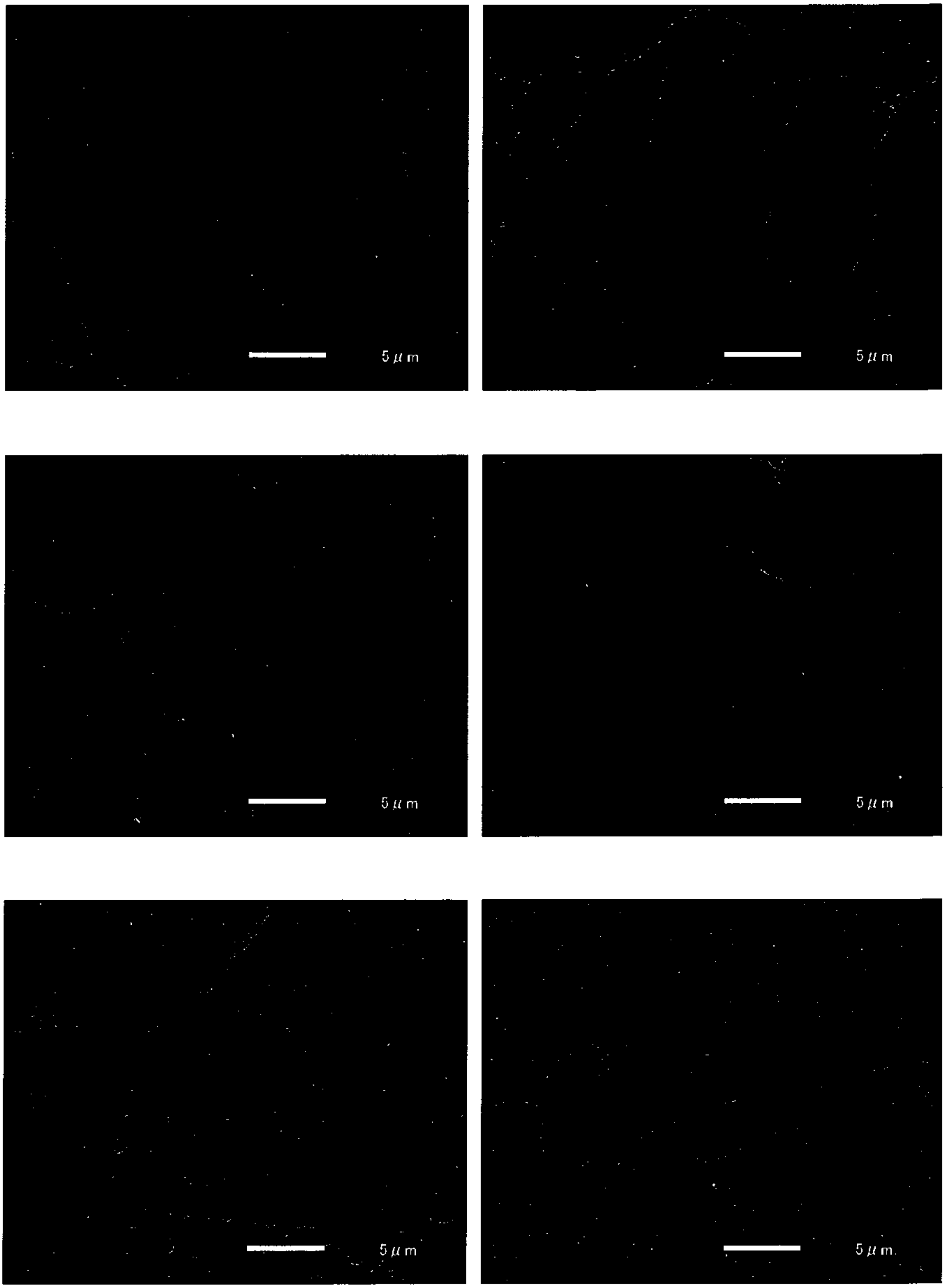


Photo I -10-9 Precipitates along grain boundary by SEM observation
Main Steam Pipe-Left (Circumferential weld, intrados : Base metal)

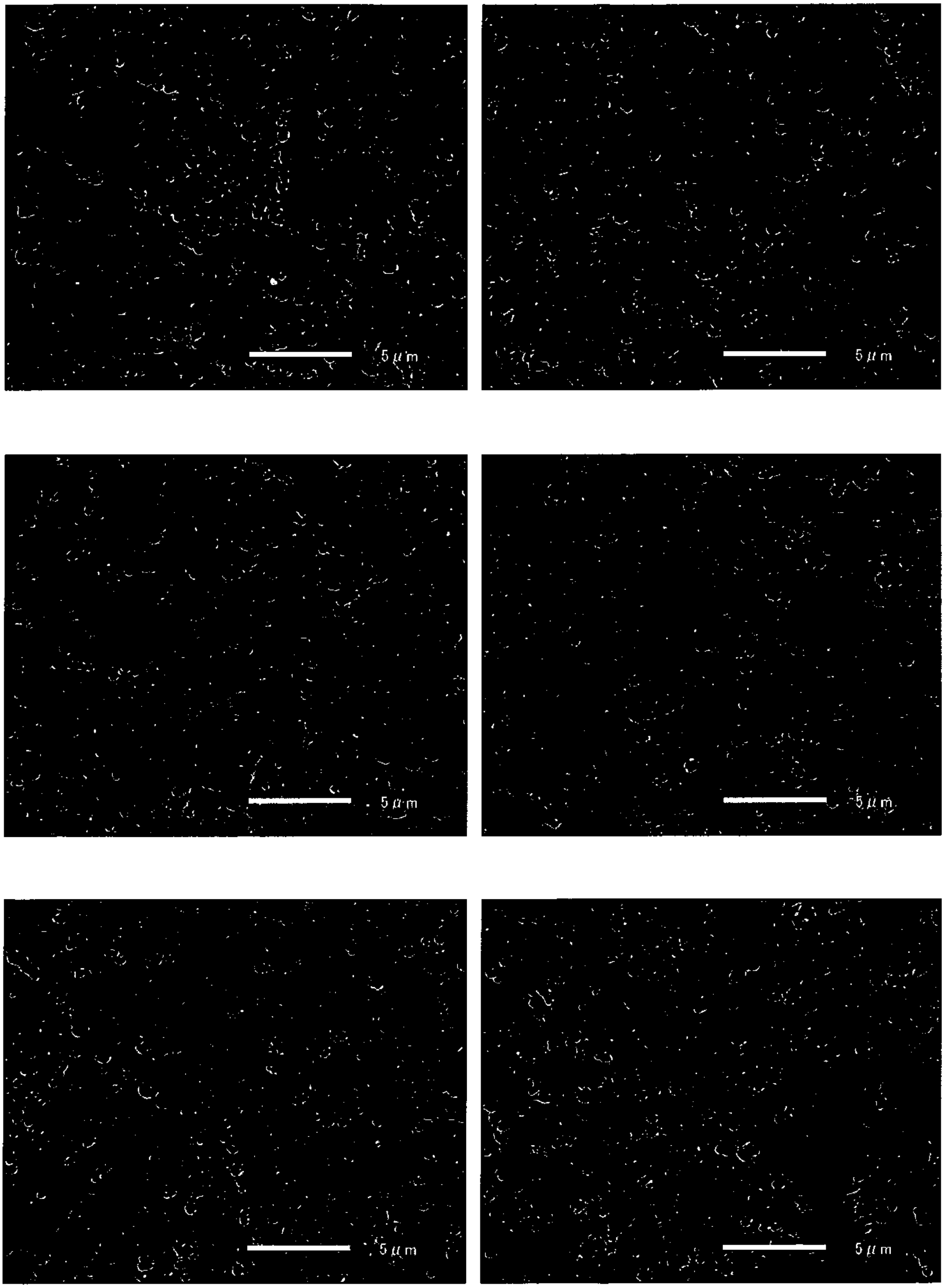


Photo I -10-10 Precipitates along grain boundary by SEM observation
Main Steam Pipe-Left (Circumferential weld, intrados : Fine grain HAZ)

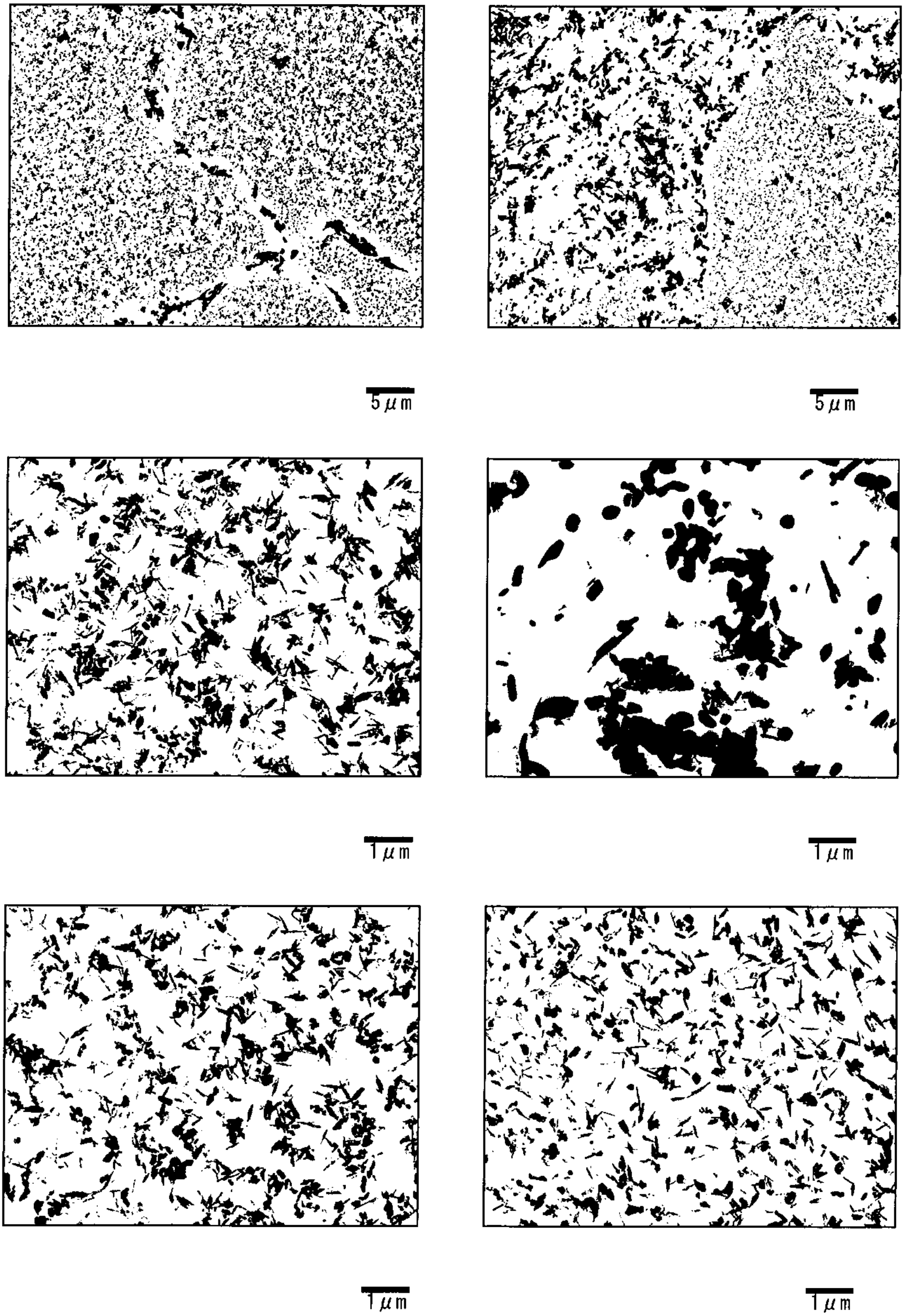


Photo I -10-11 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left (Circumferential weld, intrados : Base metal)

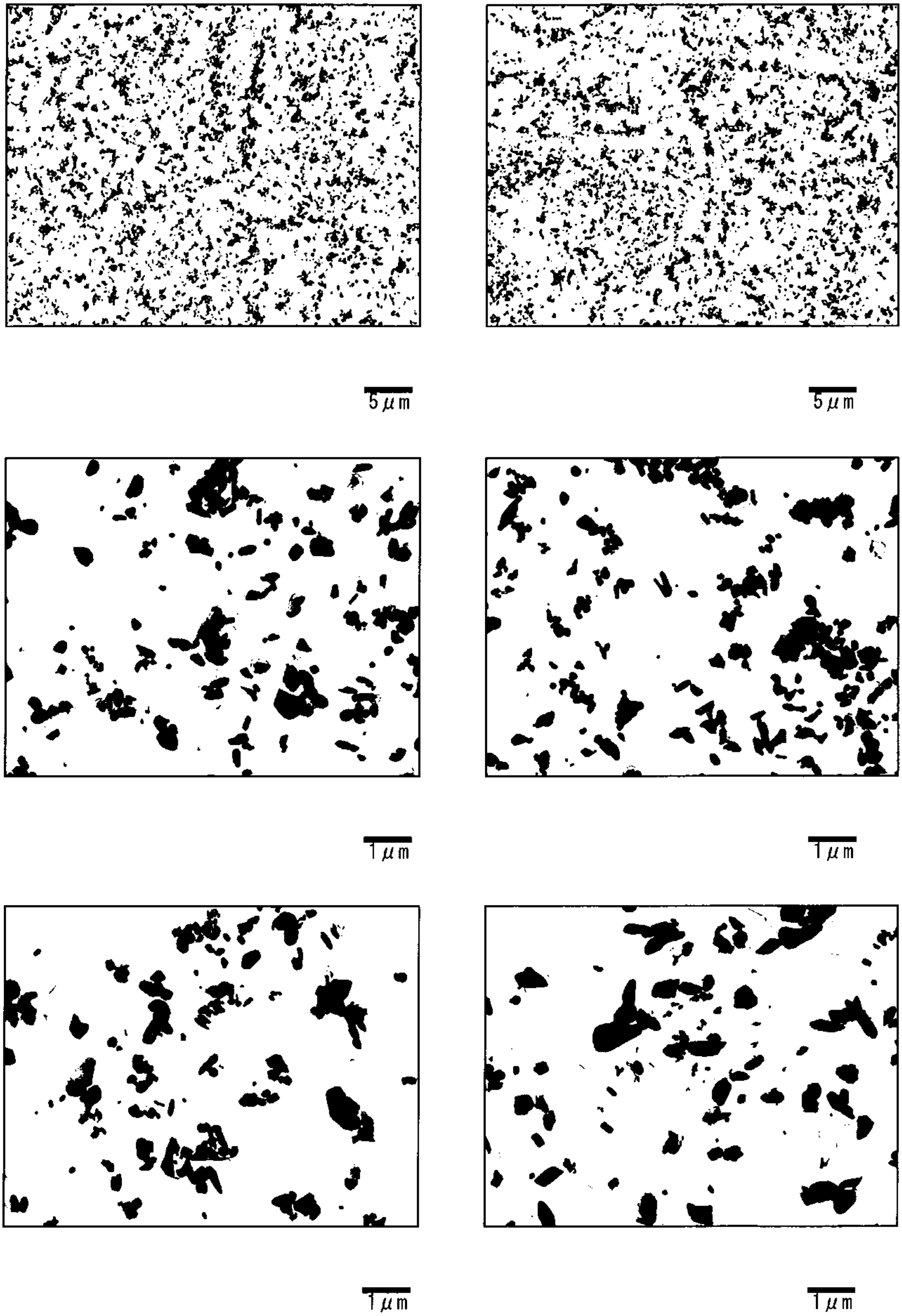


Photo I-10-12 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, intrados : Fine grain HAZ)

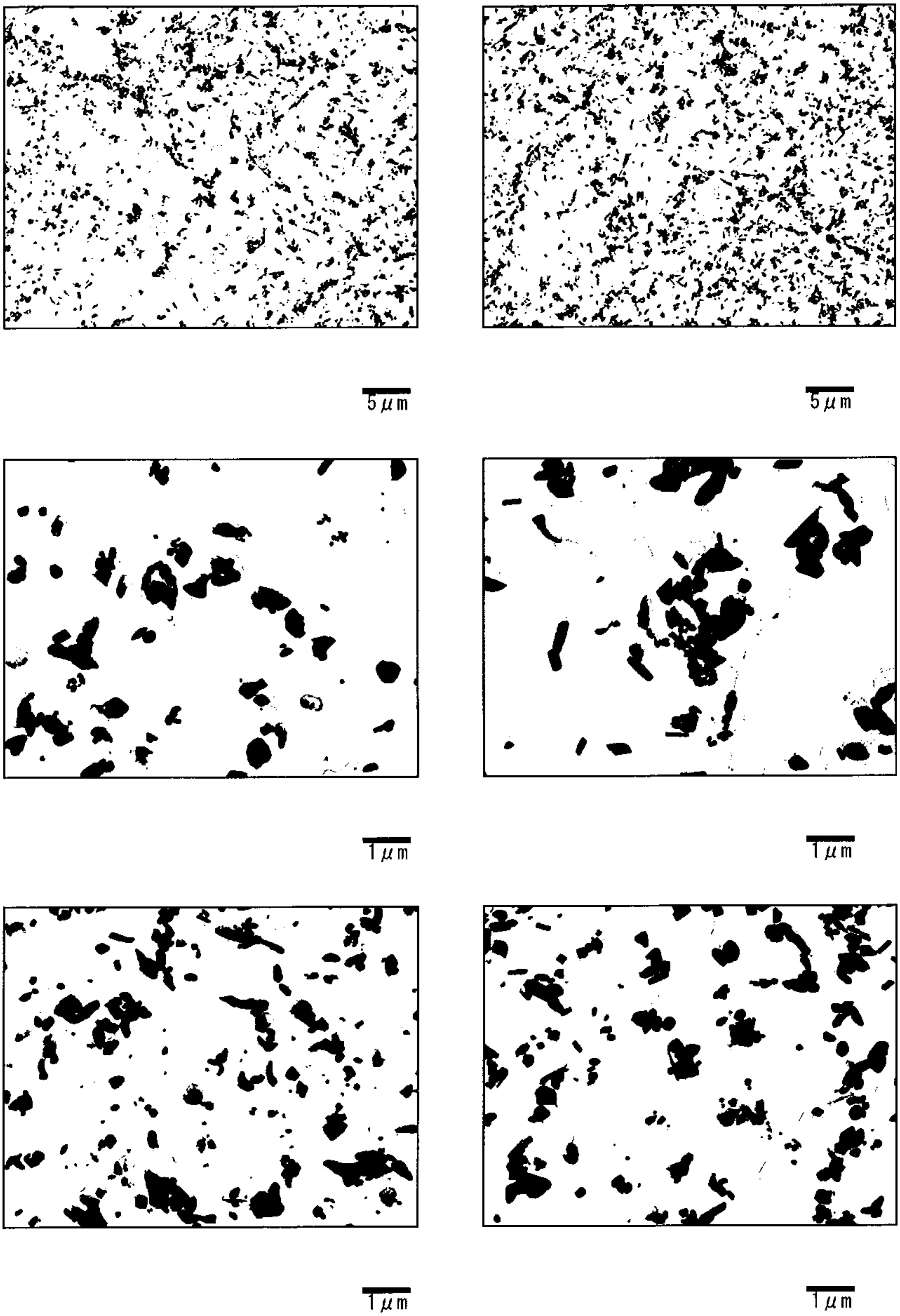


Photo I -10-13 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left(Circumferential weld, intrados : Coarse grain HAZ)

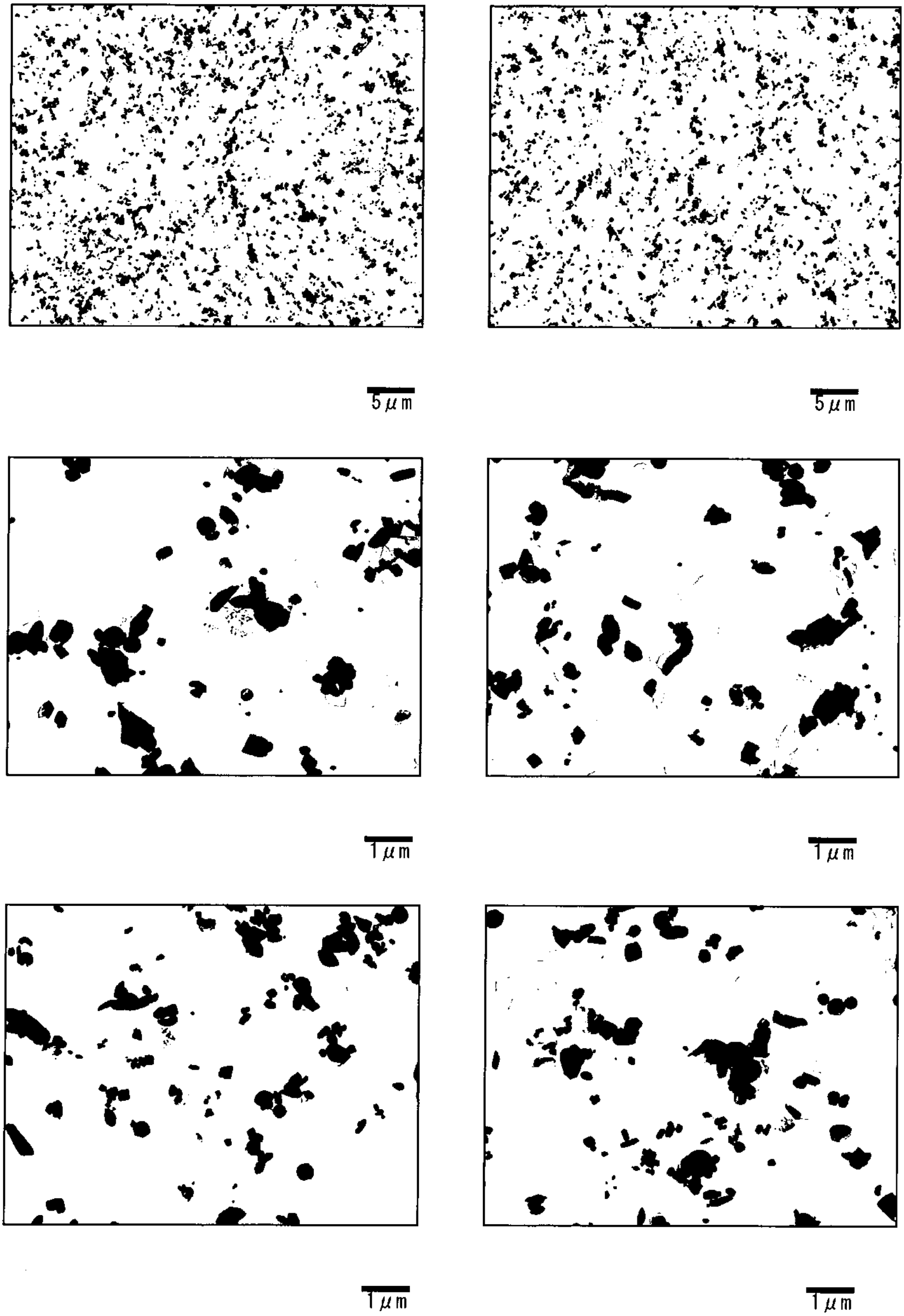
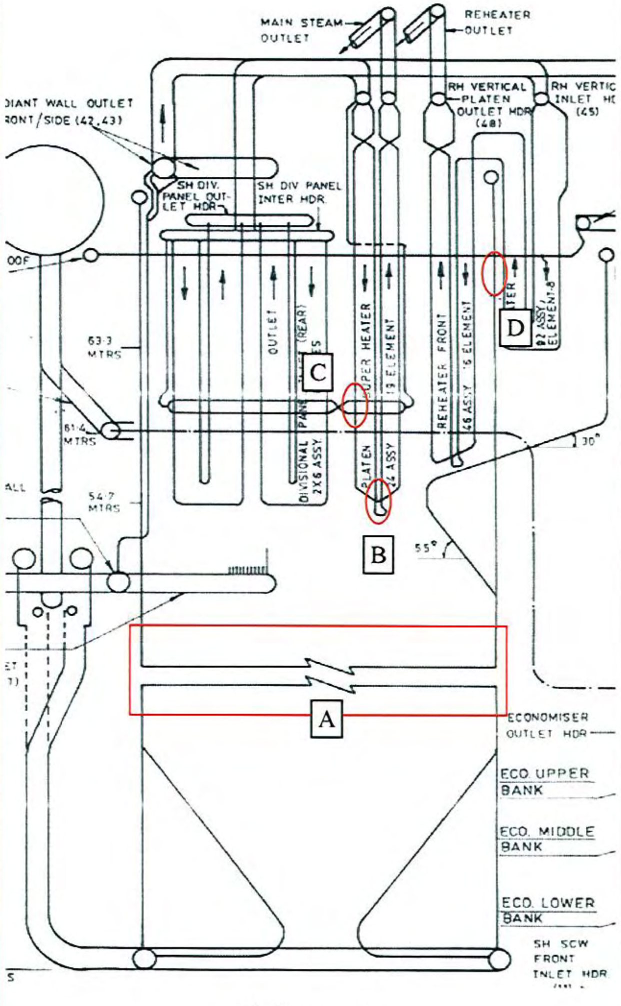


Photo I -10-14 Precipitates by TEM (Transmission electron microscope) observation
Main Steam Pipe-Left (Circumferential weld, intrados : Weld metal)

661

Table I -12 Singrauli #6 Boiler findings by visual inspection

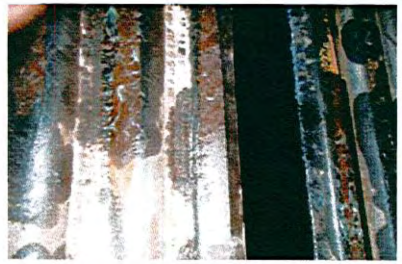


Finding portion

A: Erosion of water wall around short soot blowe

・Erosion of a number of tubes around short soot blower
(Thickness measurement conducted)

〔Min. measured value〕
Min. 3.7mm (2nd blower in forntwal first from right



B: Platen-SH Attrition of binding tube #4 and #5 (Min.2.8mm)

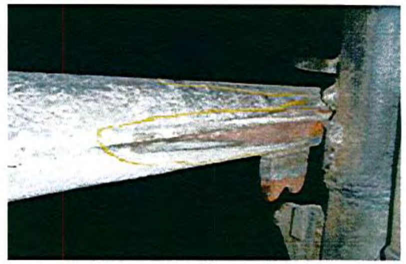
・Attrition of binding tube #4 and #5 with each othe

〔Min. measured value〕
Min.2.8mm φ63.5* 6.5mm SA213 TP347H
(Normal portion: 6.5mm)

C: Attrition of cooling spacer tube with front tube of #14 pane

・Attrition of a cooling spacer tube with front tube of #14 pane
(Thickness measurement conducted)

〔Min. measured value〕
Min.5.0mm



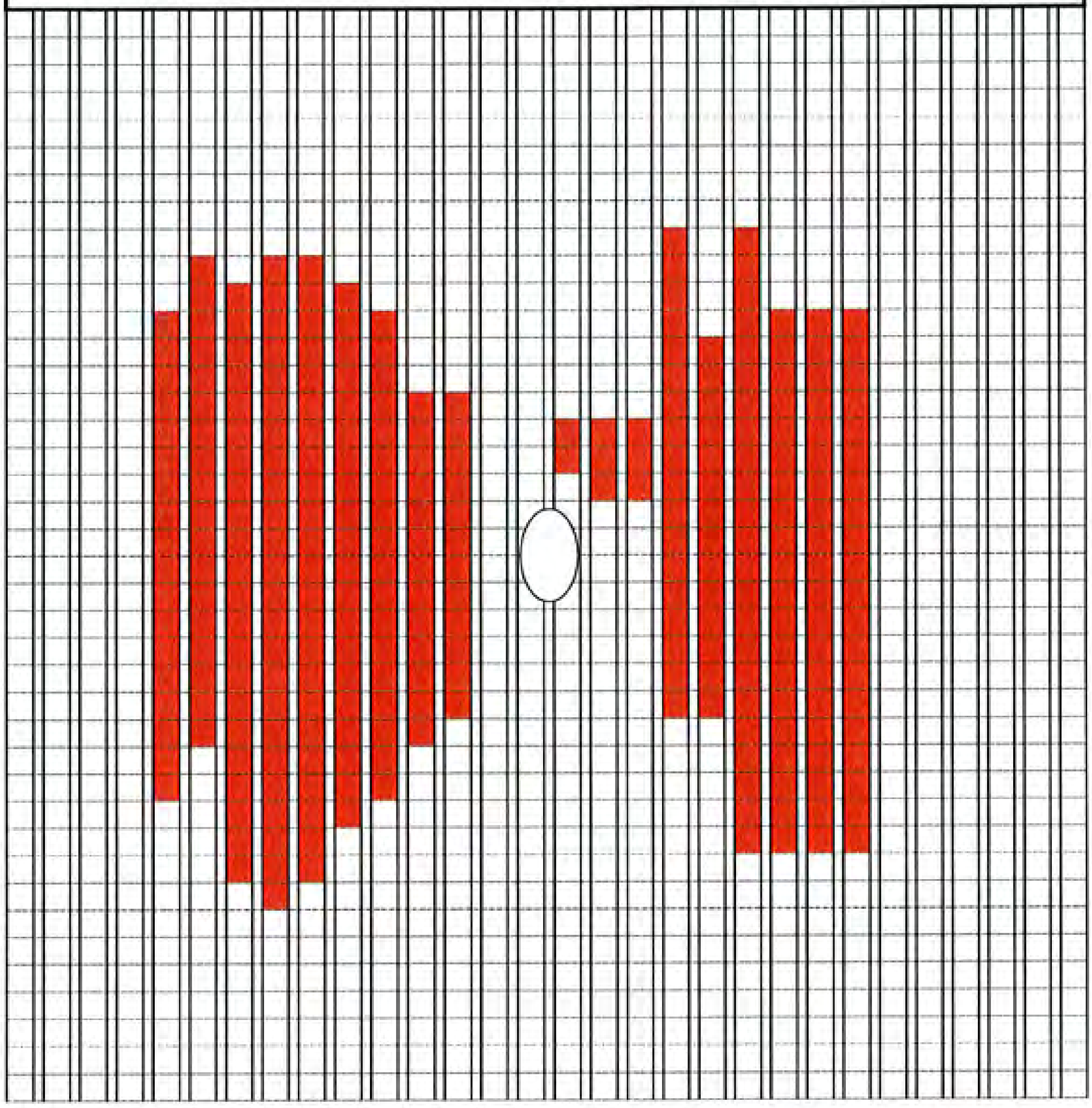
D: Erosion of screen tubes near the ceiling between front RH panel and rear RH pane

・Erosion of screen tubes at front side near the ceiling were found at left side of boiler.
(Thickness measurement not conducted)

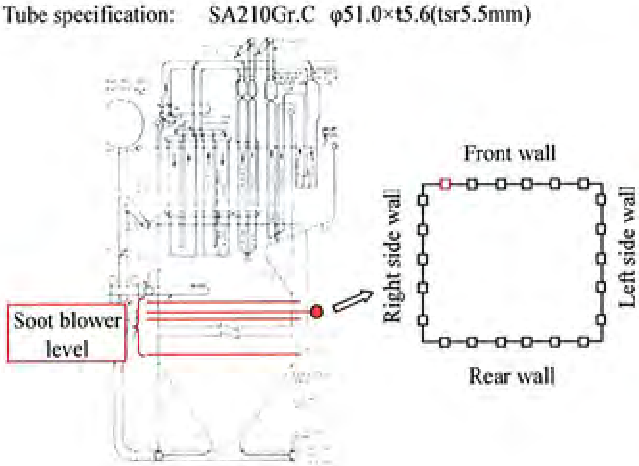
Table I-13 (Singrauli) WATER WALL Front wall Thickness Measurement Results

Tube number from sootblower center veiwed from furnace inside

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Min. value in thin portion (mm)					5.3	5.4	4.9	4.5	4.4	3.7	4.1	5.2	3.8			4.3	4.9	5.3	4.0	5.4	4.2	4.2	4.3	4.4						

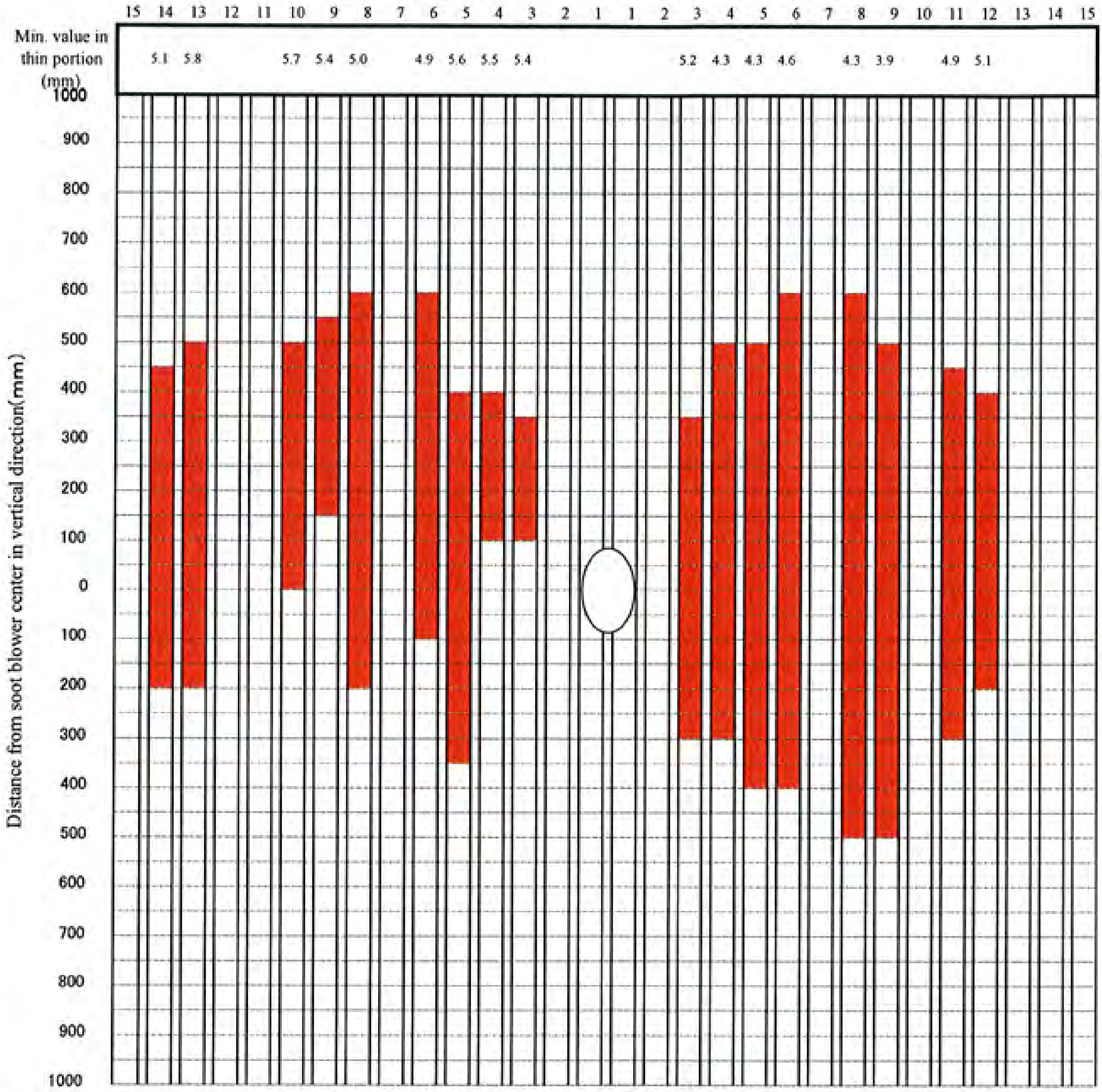


Tube specification: SA210Gr.C φ51.0×t5.6(tsr5.5mm)



206

Table Ⅰ-14 (Singrauli) WATER WALL Rear wall Thickness Measurement Results



Tube specification: SA210Gr.C φ51.0×t5.6(tsr5.5mm)

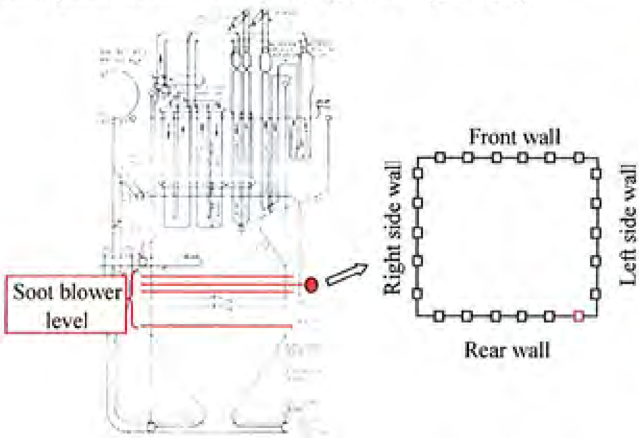
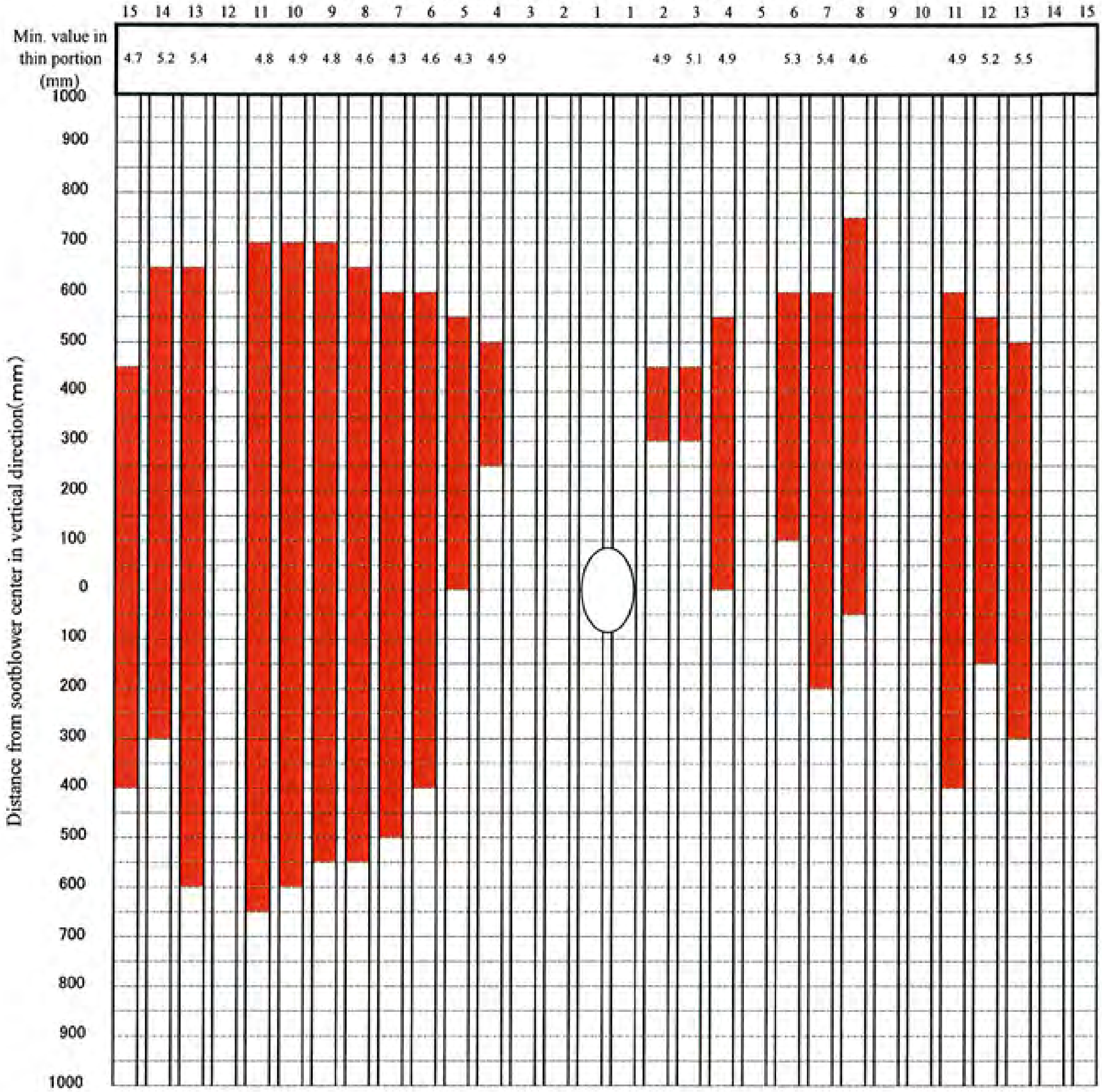
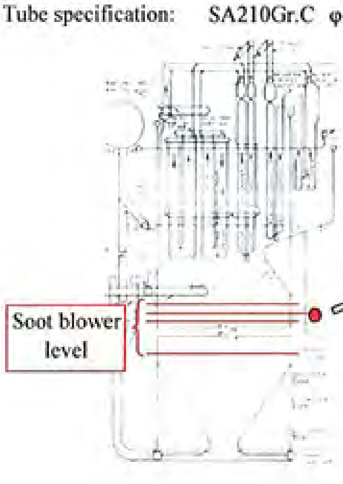
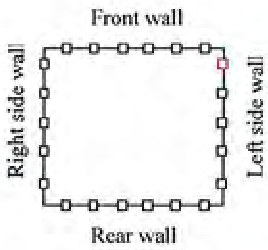


Table Ⅰ-15 （Singrauli）WATER WALL Left side wall Thickness Measurement Results



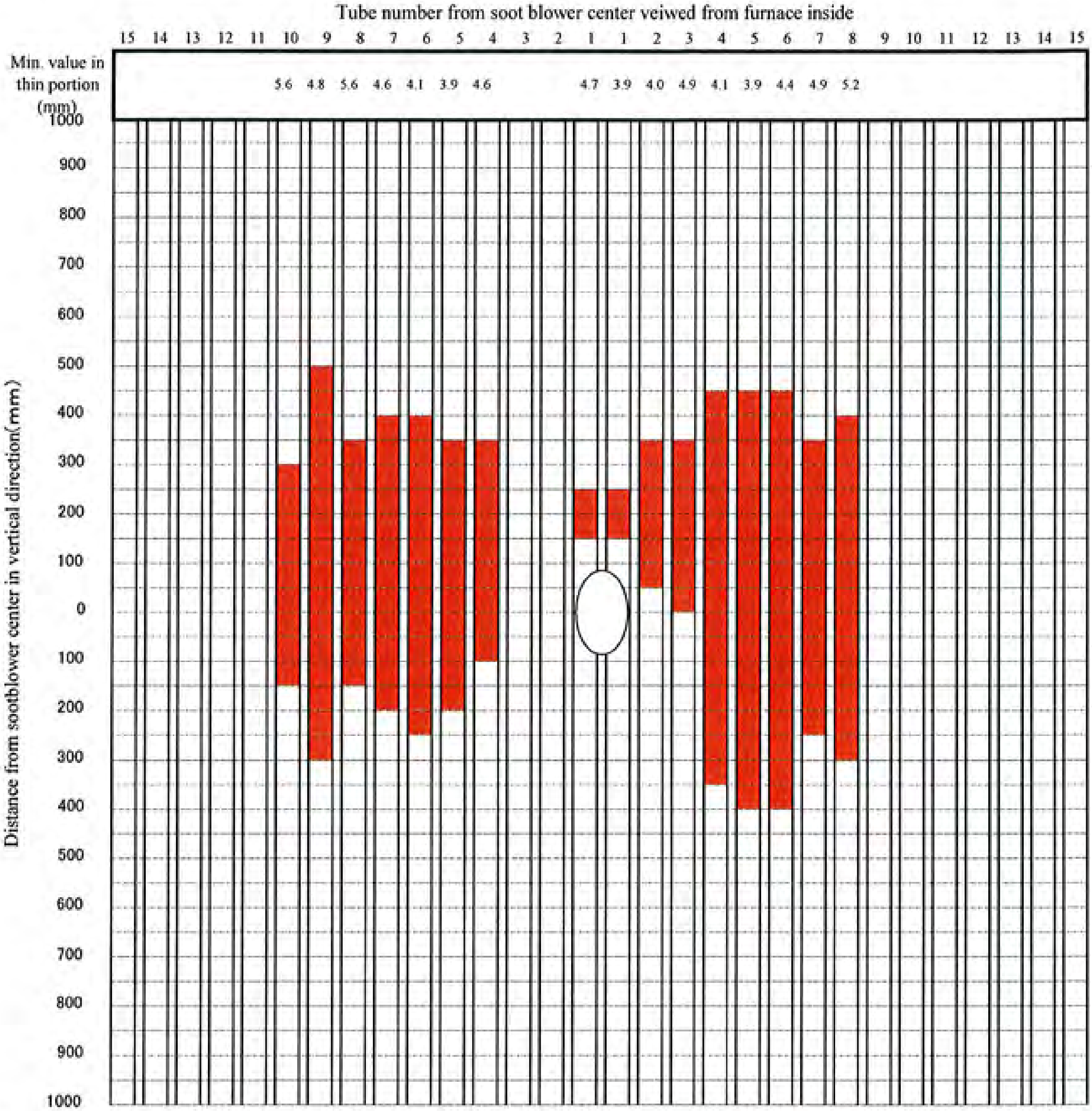
Tube specification: SA210Gr.C φ51.0×t5.6(tsr5.5mm)





202

Table Ⅰ-16 (Singrauli) WATER WALL Rightt side wall Thickness Measurement Results



Tube specification: SA210Gr.C φ51.0×t5.6(tsr5.5mm)

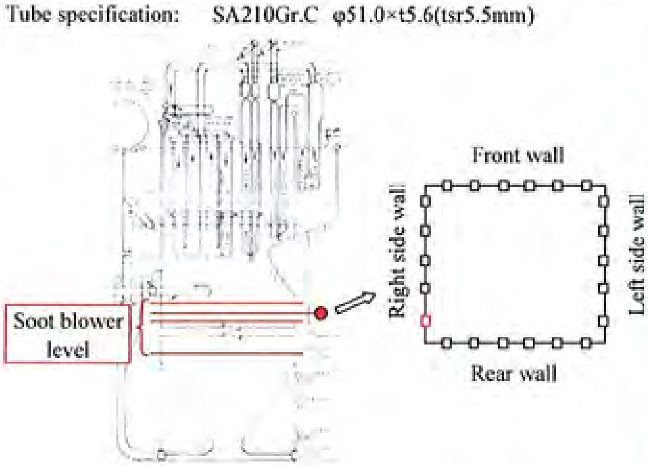
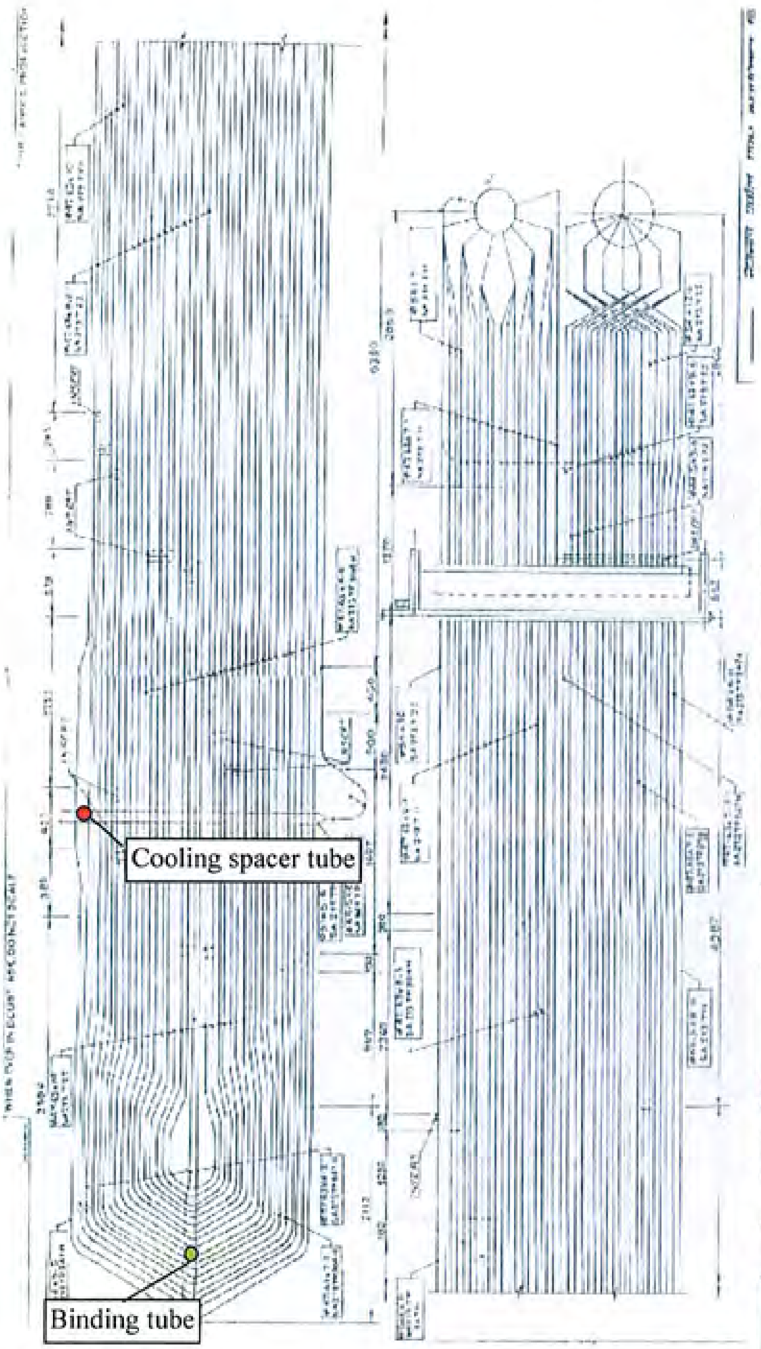


Table I-17 (Singrauli) Platen SH Thickness Measurement Results

Binding tube: SA213TP347H φ47.63×t6.3
Cooling spacer tube:



Binding tube

Panel No. (From left)	Thin point	Normal point
4R	2.8	6.5
5L	3.3	6.6

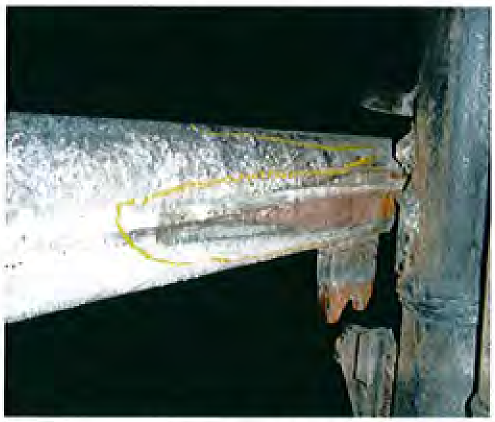
(unit: mm)

Cooling spacer tube

Attrition point with front tube of #14	5.0

(unit: mm)

Thining portion of binding tube

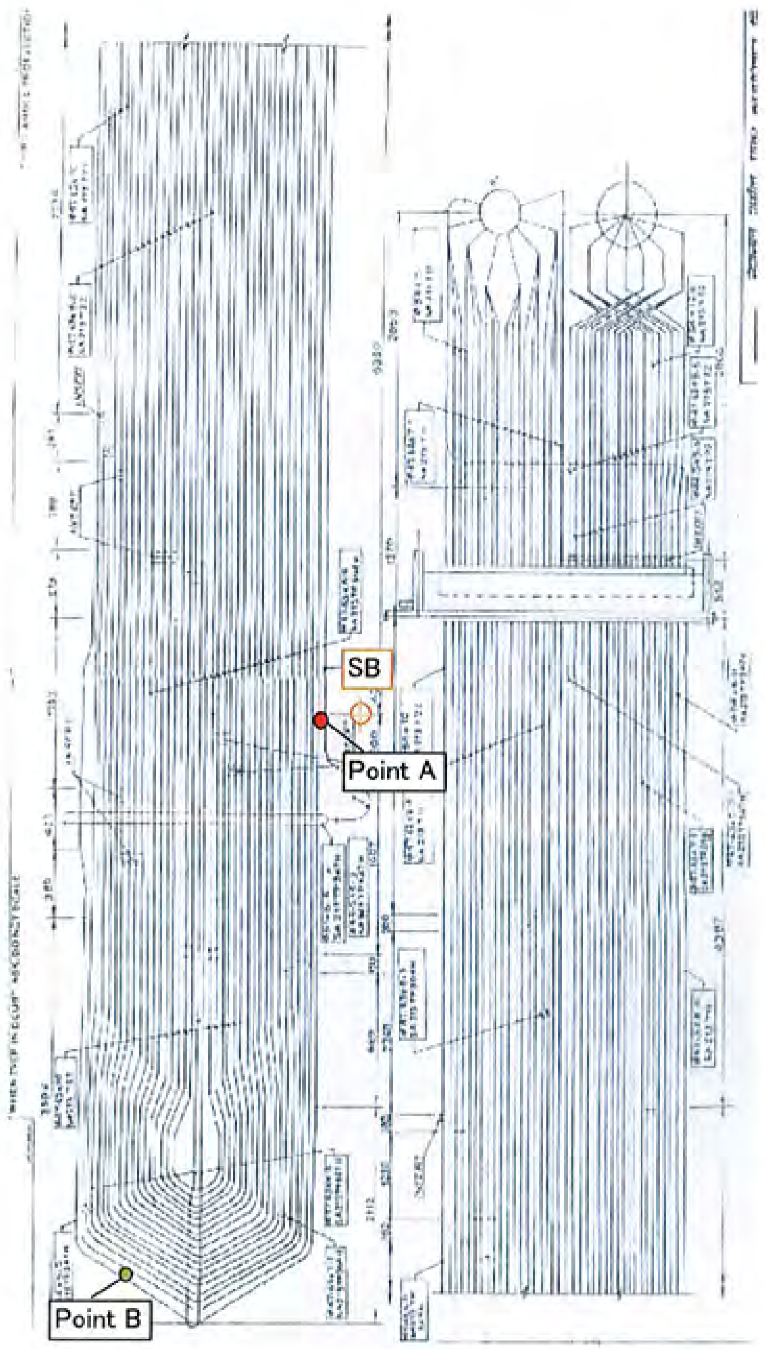


Thining portion of cooling spacer tube

Table Ⅰ-18 (Singrauli) Platen SH Thickness Measurement Results

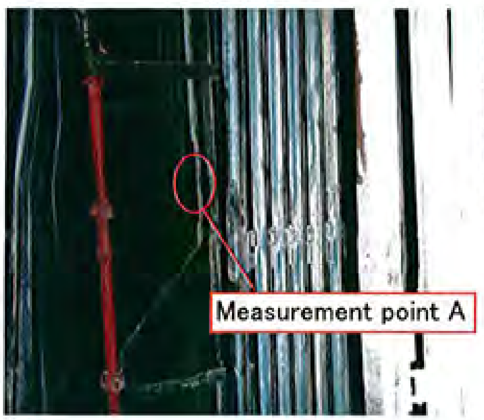
Tube specification Point A: SA213TP347H φ63.5×t6.3

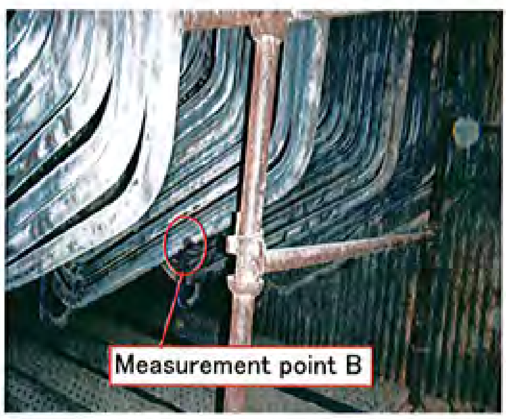
Point B: SA213TP347H φ54.0×t9.5



Panel No. (From left)	Point A ●	Point B ●
1	6.5	10.2
2	6.6	10.0
3	6.5	10.0
4	6.6	10.3
5	6.6	10.0
6	6.5	10.4
7	6.8	10.4
8	6.5	10.4
9	6.7	10.5
10	6.5	10.1
11	6.7	10.5
12	6.3	9.8
13	6.4	10.2
14	7.2	10.0
15	6.3	10.0
16	6.4	10.2
17	6.4	10.1
18	6.9	10.4
19	6.6	9.9
20	6.5	10.1
21	7.1	10.0
22	6.4	10.0
23	6.5	10.3
24	6.5	10.1

(unit: mm)

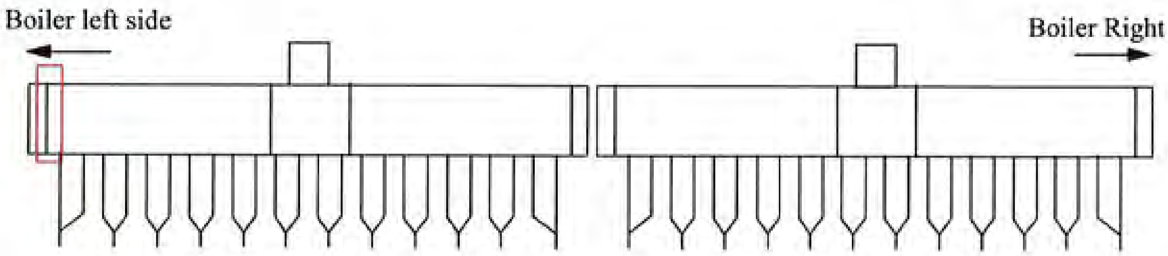


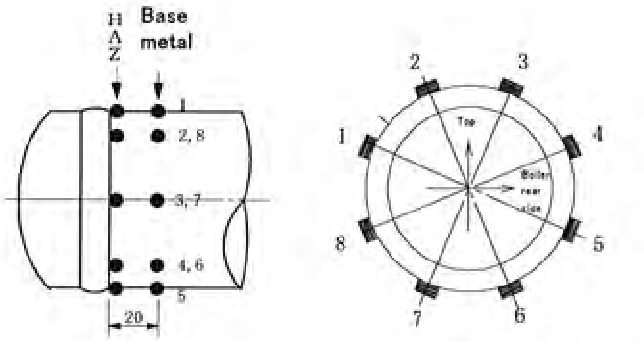


205

Table I -19 (Singrauli) PLATEN-SH Outlet Header Outside Diameter Measurement Results

Components	Material	Designed OD	Position	Region	Measured value (mm)				Averaged (mm)	(Averaged measured value-Designed OD) /Designed OD(%)
					1⇔5	2⇔6	3⇔7	4⇔8		
PLATEN SH Outlet Header	SA335 P-12	508.0mm	(Header side)	Base metal	508.03	508.36	508.75	508.95	508.52	+0.10
				HAZ	506.82	508.35	507.85	508.42	507.86	-0.03

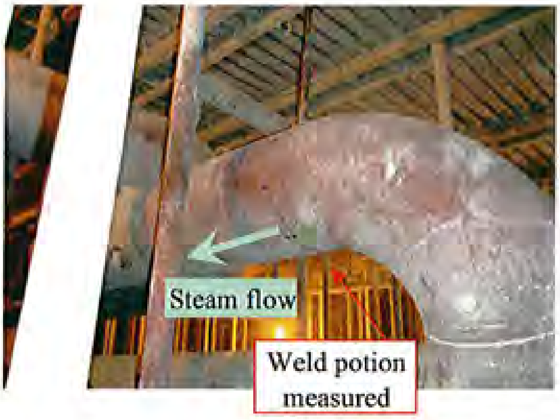




View from boiler right side

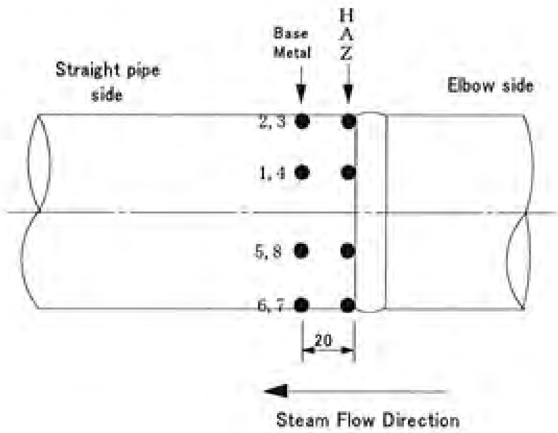
Table I -20 (Singrauli) De-Superheater Pipe Outside Diameter Measurement Results

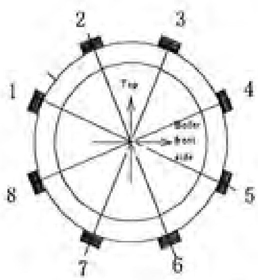
Components	Material	Designed OD	Position	Region	Measured value (mm)				Averaged (mm)	(Averaged measured value-Designed OD) /Designed OD(%)
					1⇔5	2⇔6	3⇔7	4⇔8		
De-Superheater Pipe (Right)	SA335 P-12	508.0mm	Downstream side (Straight pipe side)	Base metal	513.22	513.21	512.02	512.72	512.79	+0.94
				HAZ	511.85	512.35	511.80	511.60	511.90	+0.77
De-Superheater Pipe (Left)	SA335 P-12	508.0mm	Downstream side (Straight pipe side)	Base metal	509.87	511.60	511.41	510.32	510.80	+0.55
				HAZ	509.17	511.25	511.37	510.06	510.46	+0.48



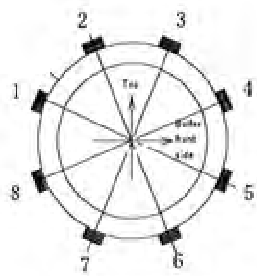
Measurement point of right De-superheater pipe

Measurement point of left De-superheater pipe





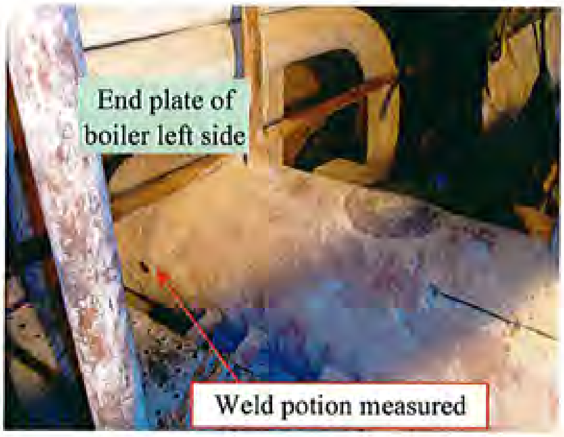
Right side: View from downstream



Left side: View from upstream

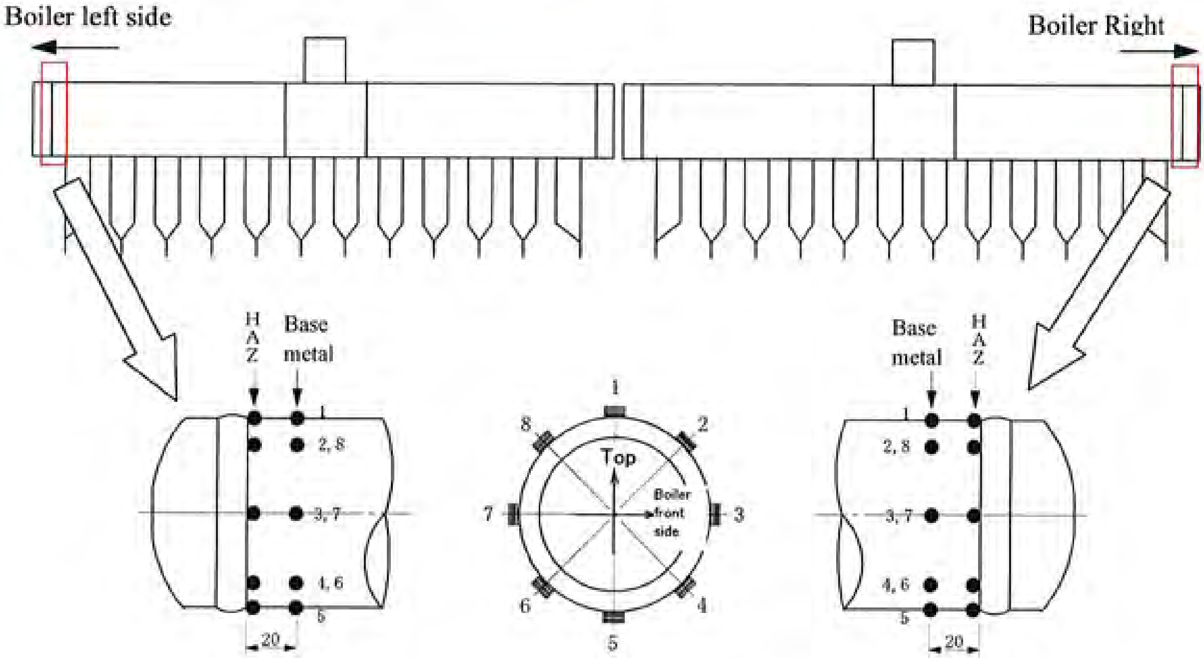
Table I -21 (Singrauli) Re-Heater Outlet Header Outside Diameter Measurement Results

Components	Material	Designed OD	Position	Region	Measured value (mm)				Averaged (mm)	(Averaged measured value-Designed OD) /Designed OD(%)
					1⇔5	2⇔6	3⇔7	4⇔8		
Re-Heater Outlet Header(Right)	SA335 P-22	558.8mm	(Header side)	Base metal	561.16	561.31	562.16	562.16	561.70	+0.52
				HAZ	560.33	561.16	562.05	561.88	561.36	+0.46
Re-Heater Outlet Header(Left)	SA335 P-22	558.8mm	(Header side)	Base metal	560.40	560.68	561.21	561.10	560.85	+0.37
				HAZ	559.47	560.64	560.55	561.00	560.42	+0.29



Measurement point of left RH outlet header

Measurement point of right RH outlet header

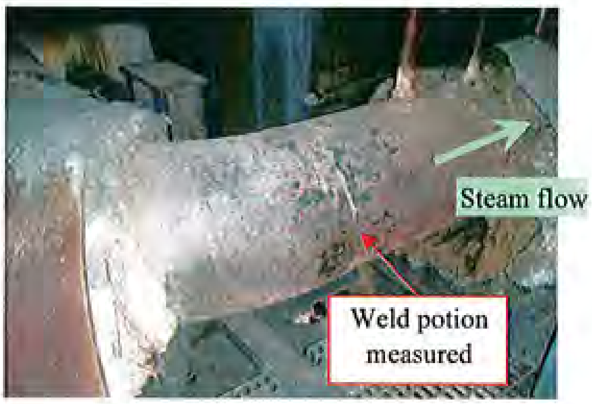


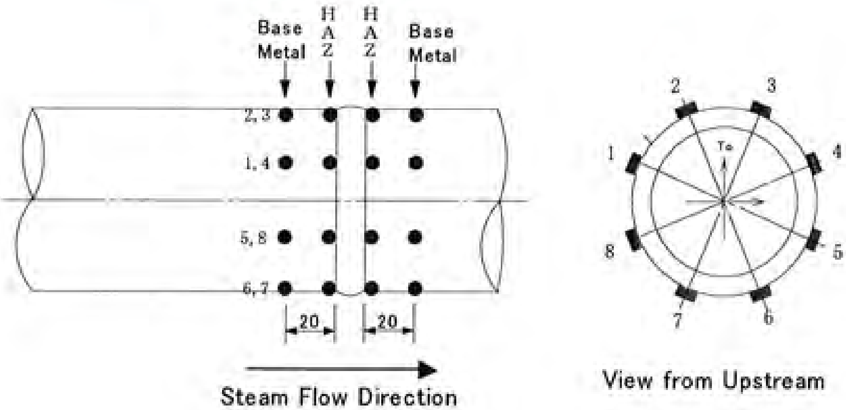
View from boiler left side

Table I -22 (Singrauli) Main Steam Pipe Outside Diameter Measurement Results

Components	Material	Designed OD	Position	Region	Measured value (mm)				Averaged (mm)	(Averaged measured value-Designed OD) /Designed OD(%)
					1⇔5	2⇔6	3⇔7	4⇔8		
MSP	SA335 P-22	520.0mm	Upstream side (Elbow side)	Base metal	521.45	525.17	527.46	531.70	526.45	+1.24*
				HAZ	520.20	520.80	522.38	521.84	521.31	+0.25*
			Downstream side (Straight pipe	Base metal	520.15	520.19	520.58	520.79	520.43	+0.08
				HAZ	520.15	520.52	519.92	520.61	520.30	+0.06

*: Upstream side value is reference because of elbow side.





Sample tube inspection〔Singrauli #6〕

Sample tube inspection and creep rupture test were carried out as one of the boiler residual life assessment items for Singrauli Super Thermal Power Station #6 unit. The results are reported as follows.

1. Unit for evaluation

Singrauli Super Thermal Power Station #6 unit

2. Sample tube for inspection

- Platen-SH tube
- RH tube (Penthouse portion, Furnace portion)

3. Operation condition

(1) Cumulative operation hours:	172,000	hours
(2) Cumulative start and stop times:	309	times

4. Summary of inspection results

(1) As a result of tube appearance observation after acid cleaning, traces of corrosion at outside surface and slightly rough condition at inside surface were observed for each sample tube.

(2) As a result of tube dimension measurement, OD of RH tubes in penthouse and in furnace was less than designed value, the thickness of RH tubes in penthouse was less than designed value.

(3) As a result of steam oxide scale examination, steam oxide scale was adhering evenly by cross sectional observation for RH tube in penthouse and in furnace, unevenly for Platen-SH tube.
Average thickness of steam oxide scale mainly consisting of Fe and O was remarkably larger in RH tube (in penthouse) than in Platen-SH tube and RH tube (in furnace).

(4) As a result of hardness measurement, the hardness values were stable in circumferential direction,though measured values were out of the normal value of virgin material by Japanese steel manufacturer.

(5) As a result of creep rupture test, the evaluated residual life of Platen-SH tube was 290,000 hours for base metal, 150,000hours for weld joint at equivalent temperature 553℃ estimated by comparison with the average creep rupture data of NIMS.
The evaluated residual life of RH tube in furnace was 670,000 hours for base metal and 610,000 hours for weld joint at equivalent temperature 551℃ estimated by comparison with the average creep rupture data of NIMS.
Each portion has enough evaluated residual life at present, with the min. evaluated residual life of 150,000 hours for weld joint portion of Platen-SH tube.

(6) As a result of microstructure comparison method, the evaluated residual life was 82,000 hours for RH tube (in furnace), 520,000 hours for RH tube (in penthouse) and 1,300,000 hours for Platen-SH tube.

5. Sample tube specification

Sample tube specification is shown in Table I -30.

Table I -30　Sample tube specification

Sample	Material	Designed ODxt(mm)	Designed Temperature(℃)	Designed Pressure (MPa)
Platen-SH　#12-3	SA213T11※	ϕ 47.63xt8.6	Not available	17.46
	SA213T11	ϕ 47.63xt10.0	Not available	
RH　#3-1 (in penthouse)	SA213T22※	ϕ 54.0xt5.6	540	5.27
	SA213T22	ϕ 54.0xt5.6	540	
RH　#14-5 (in furnace)	SA213T22	ϕ 54.0xt4.5	Not available	5.27
	SA213T11※	ϕ 54.0xt4.0	Not available	

※ : Chemical composition analysis was conducted as shown below.
The material of Platen-SH#12-3 appeared to be SA213T11 by chemical composition analysis, though the material specification was supposed to be SA213T22 for Platen-SH#12-3 according to the drawing.

Chemical composition analysis results by spark discharge optical emission analysis (wt%)

Sample tube	C	Si	Mn	P	S	Cr	Mo
Platen-SH#12-3	0.10	0.53	0.38	0.026	0.012	1.14	0.46
RH #3-1 (in penthouse)	0.10	0.28	0.45	0.013	0.008	2.20	0.95
RH #14-5 (in furnace)	0.10	0.67	0.41	0.006	0.008	1.30	0.58
SA213T11 (JIS-STBA23)	≦0.15	0.50～1.00	0.30～0.60	≦0.030	≦0.030	1.00～1.50	0.45～0.65
SA213T22 (JIS-STBA24)	≦0.15	≦0.50	0.30～0.60	≦0.030	≦0.030	1.90～2.60	0.87～1.13

6. Inspection item and inspected portion

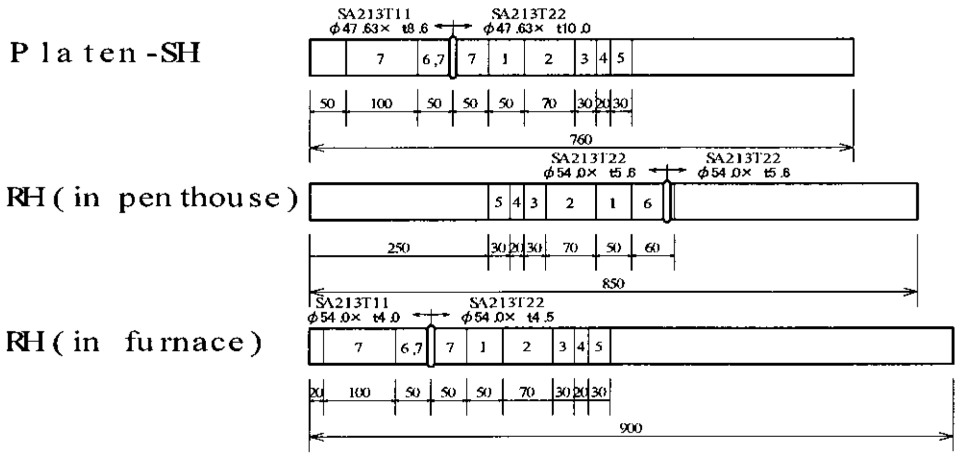
Inspection item and inspected portion are shown in Table I -31.

Table I -31 Inspection item

Sample tube	Inspection item						
	1	2	3	4	5	6	7
	Outer surface appearance	Internal surface appearance	Tube dimension · Hardness	Metallography	Scale analysis	RLA by microstructure degradation	Creep rupture test
Platen-SH	○	○	○	○	○	○	○
RH(in penthouse)	○	○	○	○	○	○	–
RH(in furnace)	○	○	○	○	○	○	○

Sample tube appearance and sampling location are shown in Photo I -11.

Sampling portion for each inspection item is shown in Fig I -11.



1: Outer surface appearance 2: Internal surface appearance 3: Tube dimension · Hardness 4: Metallography

5: Scale thickness, EPMA analysis, 6: RLA by microstructural comparison method 7: Creep rupture test

Fig I -11 Sampling portion for each inspection item

7. **Inspection results**

(1) Tube appearance

a. Tube appearance from outside (Photo I -12)

- Hard oxide scale was adhering for each sample tube outer surface, with light brown color in Platen-SH tube, red brown color in RH tube (penthouse) and dark brown color in RH tube (furnace).
- Traces of corrosion were observed in each sample tube outside surface after acid cleaning.

b. Tube appearances of sample tubes from inside after removal of steam oxide scale (Photo I -13～18)

(Platen SH tube)

- Internal surface of both front and rear side were covered with gray and red color steam oxide scale.
- Slight rough internal surface was observed after acid cleaning.

(RH tube （in penthouse, furnace）)

- Internal surface of both front and rear side were covered with gray color steam oxide scale with scale exfoliation partially observed on rear side.
- Slightly rough internal surface was observed after acid cleaning.

(2) Tube dimension measurement (Table I -32, Fig I -12)

a. OD measurement

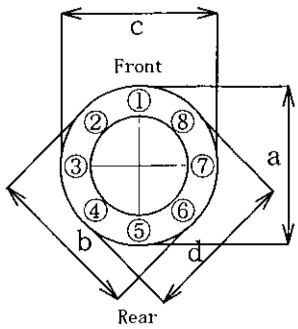
OD of RH tubes in penthouse and furnace were measured to be less than designed values.

b. Thickness measurement

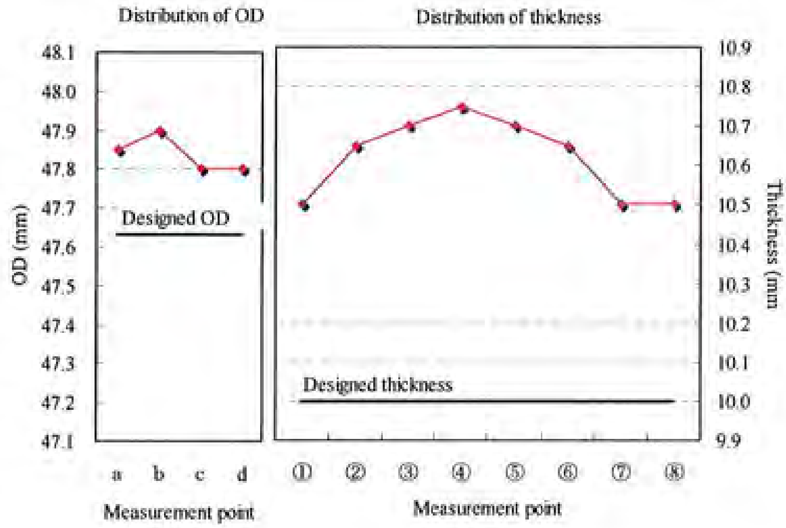
Thickness of RH tubes in penthouse was measured to be less than designed values.

Table I -32 Tube dimension measurement results

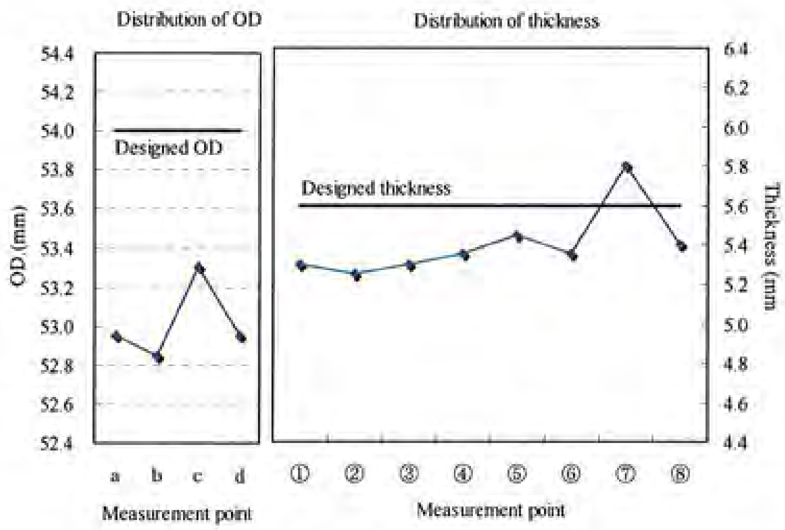
Sample tube	Specification	OD (mm)			Thickness (mm)							
		Direction	OD	ID	①	②	③	④	⑤	⑥	⑦	⑧
Platen-SH	Φ47.63×t10.0	a	47.85	26.60	10.50				10.70			
		b	47.90	26.60		10.65				10.65		
		c	47.80	26.60			10.70				10.50	
		d	47.80	26.60				10.75				10.50
RH(in penthouse)	Φ54.0×t5.6	a	52.95	42.25	5.30				5.45			
		b	52.85	42.25		5.25				5.35		
		c	53.30	42.15			5.30				5.80	
		d	52.95	42.15				5.35				5.40
RH(in furnace)	Φ54.0×t4.5	a	53.75	43.65	5.10				5.05			
		b	54.00	43.95		4.95				5.10		
		c	54.00	43.95			4.90				5.20	
		d	53.75	43.65				4.95				5.15



Platen-SH



RH(in penthouse)



RH(in furnace)

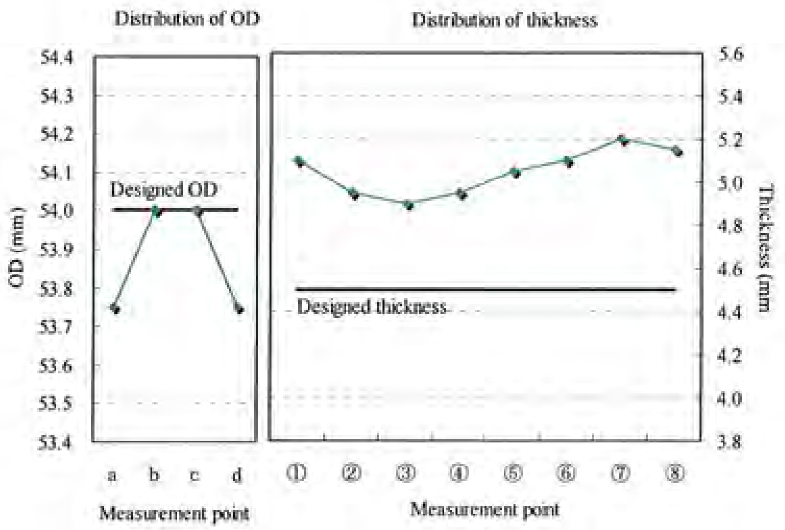


Fig I -12 Tube dimension measurement results

(3) Steam oxide scale adhesion on internal surface

a. Cross sectional observation of internal surface (Photo I -19)

(Platen SH tube)

- Steam oxide scale was adhering unevenly by cross sectional observation.
- Corrosion in metal surface was observed with rugged interface between steam oxide scale and metal.

(RH tube in penthouse)

- Steam oxide scale was adhering evenly by cross sectional observation with dual layer consisting of dense inner layer and slightly porous outer layer.

(RH tube in furnace)

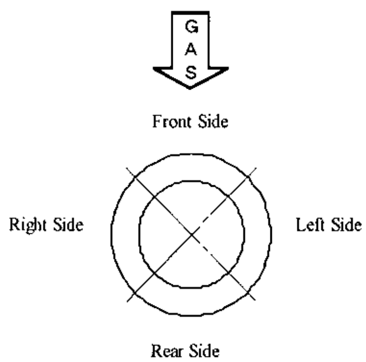
- Steam oxide scale was adhering evenly by cross sectional observation with the thicker scale on left and right side surfaces than the scale on front and rear side.

b. Thickness measurement of steam oxide scale on internal surface (Table I -33)

Average thickness of steam oxide scale was remarkably larger in RH tube (in penthouse) than in Platen-SH tube and RH tube (in furnace).

Table I -33 Steam oxide scale thickness measurement results

Sample tube	Position	Scale thickness (μ m)	
		Average among 90°range	Max. among 90° range
Platen-SH	Front Side	89.2	109.8
	Right Side	85.3	102.4
	Rear Side	74.7	96.8
	Left Side	82.8	125.0
RH (in penthouse)	Front Side	439.6	475.7
	Right Side	447.9	479.0
	Rear Side	381.4	453.0
	Left Side	458.0	476.0
RH (in furnace)	Front Side	32.9	41.9
	Right Side	68.9	96.8
	Rear Side	65.4	90.3
	Left Side	34.5	41.3



c. EPMA analysis of steam oxide scale on internal surface (Fig. I -13~24, Table I -34)

Mainly iron oxide scale was formed since Fe and O were remarkably detected.

- In Platen-SH tube, Fe, Cr and Mo were detected as tube material elements and O, P, Ca, Zn as the other detected elements.
- In RH tube (in penthouse), Fe, Cr and Mo were detected as tube material elements, and O as the other detected element.
- In RH tube (in furnace), Fe, Cr and Mo were detected as tube material elements, and O, P, Na, Mn as the other detected element.

Table I -34 Elements detected by EPMA analysis

Sample tube	Position	Element													
		O	S	P	N	Na	Si	Ca	Mn	Fe	Ti	Cr	Ni	Zn	Mo
Platen-SH	Front Side	■		■				■		■		■		■	■
	Right Side	■		■				■		■		■		■	■
	Rear Side	■		■				■		■		■		■	■
	Left Side	■		■				■		■		■		■	■
RH (in penthouse)	Front Side	■								■		■			■
	Right Side	■								■		■			■
	Rear Side	■								■		■			■
	Left Side	■								■		■			■
RH (in furnace)	Front Side	■								■		■			■
	Right Side	■								■		■			■
	Rear Side	■		■		■			■	■		■			■
	Left Side	■								■		■			■

■ : Elements detected clearly

(4) Hardness measurement (Fig. I -25~24, Table I -35)

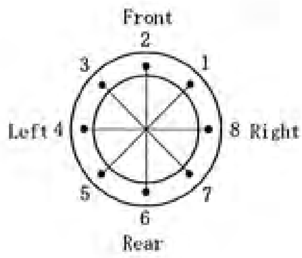
- The hardness of RH tube (in penthouse, SA213T22) was lower than the normal value of virgin material by Japanese steel manufacturer.
- The hardness of Platen-SH tube (SA213T11) and RH tube (in furnace, SA213T11) were higher than the normal value of virgin material by Japanese steel manufacturer.

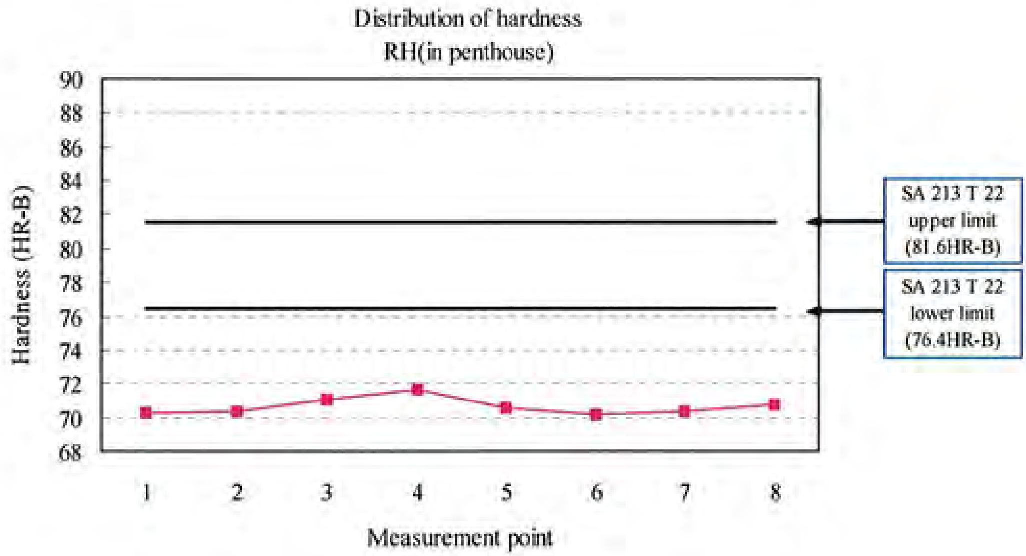
Table I -35 Hardness measurement results

(unit:HR-B)

Sample tube	Marterial	1	2	3	4	5	6	7	8
Platen-SH	SA 213 T 11	88	88	86	86	87	87	88	87
RH (in penthouse)	SA 213 T 22	70	70	71	72	71	70	70	71
RH (in furnace)	SA 213 T 11	81	82	83	82	82	82	83	82

Hardness value of vigin material by fabricator : SA 213 T 22;76.4~81.6(HR-B)
SA 213 T 11;73.4~78.4(HR-B)





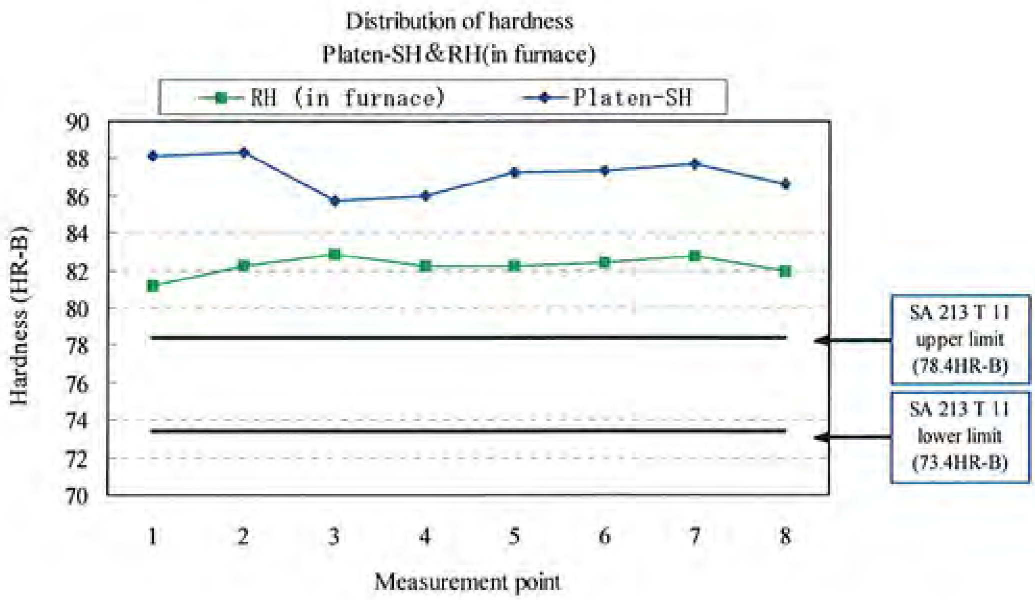


Fig I -25 Hardness measurement results

(5) Metallographic observation

Microstructure observation results at cross section of sample tube were shown in Photo I -20～25.

(Platen-SH tube (SA 213 T11))

- ➢ Microstructural degradation with disintegration of pearlite structure and precipitation in ferrite grain was not observed.

(RH tube in penthouse and furnace (SA 213 T11))

- ➢ Microstructural degradation with disintegration of pearlite structure was observed.

(6) Creep rupture test

a. Test condition

The creep test condition is shown in Table I -36. The shape of test specimens is shown in Fig. I -26

3 specimens were cut out from each of base metal portion and weld portion in Platen-SH tube and RH tube(in furnace) with a set of three test conditions for each portion.

As the shape of test specimens, φ 6mm round bar specimen was applied for Platen-SH tube and arc shaped specimen with the weld reinforcement left for RH thin-walled tube (in furnace) .

Table I -36 Creep test condition

Sample tube	Portion	Material	Test condition Tem. (°C)	Test condition Stress (MPa)	Shape of specimen
Platen-SH	Base Metal	SA213T11	665	49.0	φ6mm round bar
			665	63.7	
			700	38.3	
	Weld Metal	SA213T11	665	49.0	
			665	63.7	
			700	38.3	
RH(in furnace)	Base Metal	SA213T11	665	44.1	Arc shaped
			665	58.8	
			700	27.9	
	Weld Metal	SA213T11	665	44.1	
			665	58.8	
			700	27.9	

φ 6mm round bar　　　Ark shaped

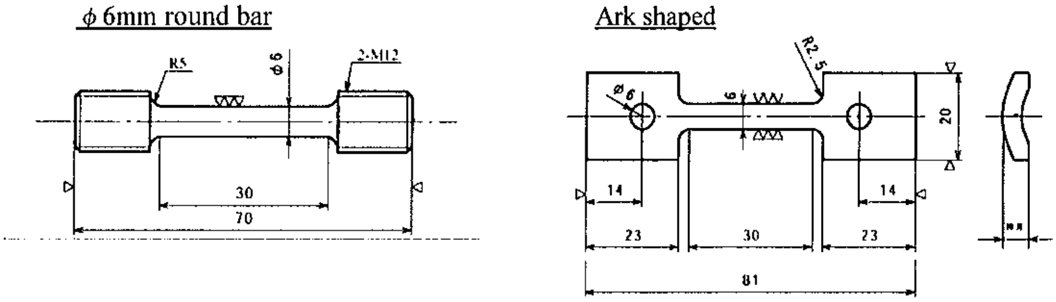
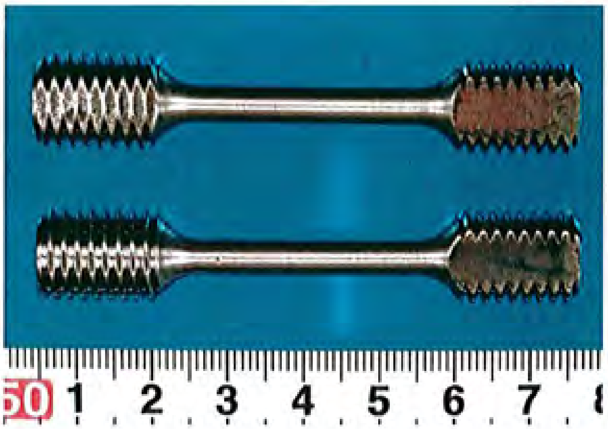


Fig I -26　Shape of creep rupture test specimens

Test specimens before and after creep rupture test in Platen-SH tube

Before machining ⇒

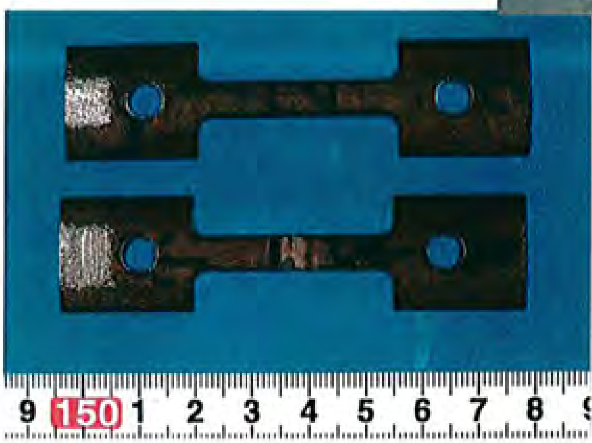


After machining ↑

After creep rupture test ↑

Test specimens before and after creep rupture test in RH tube (in furnace)

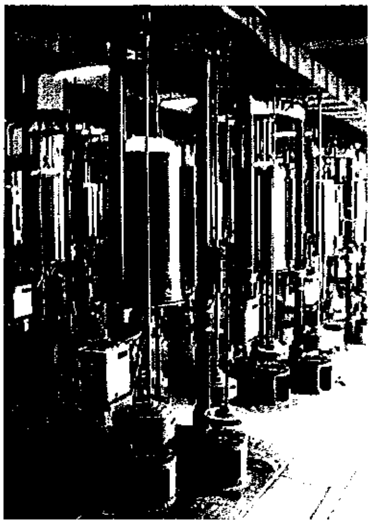
Before machining ⇒



After machining ↑

After creep rupture test ↑

Creep rupture testing machine ⇒



b. Test results

Test result is shown in Table I -37-1. All specimens had ruptured for each test condition.

Table I -37-1 Creep rupture test results (Platen-SH)

Component		Material	Test condition Temp. T(℃)	Test condition Stress (MPa)	Rupture time t (h)	LMP* C=19.95	Fracture elongation (%)	Reduction of area (%)
Platen-SH	Base Metal	SA 213 T11	665	49.0	187.7	20,852	102	97
			665	63.7	48.7	20,302	87	94
			700	38.3	76.1	21,248	88	94
	Weld Metal	SA 213 T11	665	49.0	149.0	20,758	36	92
			665	63.7	39.0	20,212	44	92
			700	38.3	43.5	21,012	35	95

* LMP=(273.15+T) (C+log t)

Table I -37-2 Creep rupture test results (RH in furnace)

Component		Material	Test condition Temp. T(℃)	Test condition Stress (MPa)	Rupture time t (h)	LMP* C=17.52	Fracture elongation (%)	Reduction of area ** (%)
RH(in furnace)	Base Metal	SA 213 T11	665	44.1	457.0	18,933	53	57
			665	58.8	139.2	18,448	62	63
			700	27.9	319.4	19,488	39	55
	Weld Metal	SA 213 T11	665	44.1	310.9	18,776	20	52
			665	58.8	69.3	18,164	13	53
			700	27.9	296.8	19,457	16	56

* LMP=(273.15+T) (C+log t)

** Reduction of area for RH tube is regarded as reference, because the value was evaluated by reduction of width of arc shaped specimen.

The comparison of the test results with the creep rupture data of virgin materials by NIMS (National Institute for Materials Science) is shown in Fig. I -27.

The test results for base metal and weld joint in Platen-SH tube indicate the lower creep rupture strength than NIMS data, and those in RH tube (in furnace) indicate almost same creep rupture strength as NIMS data.

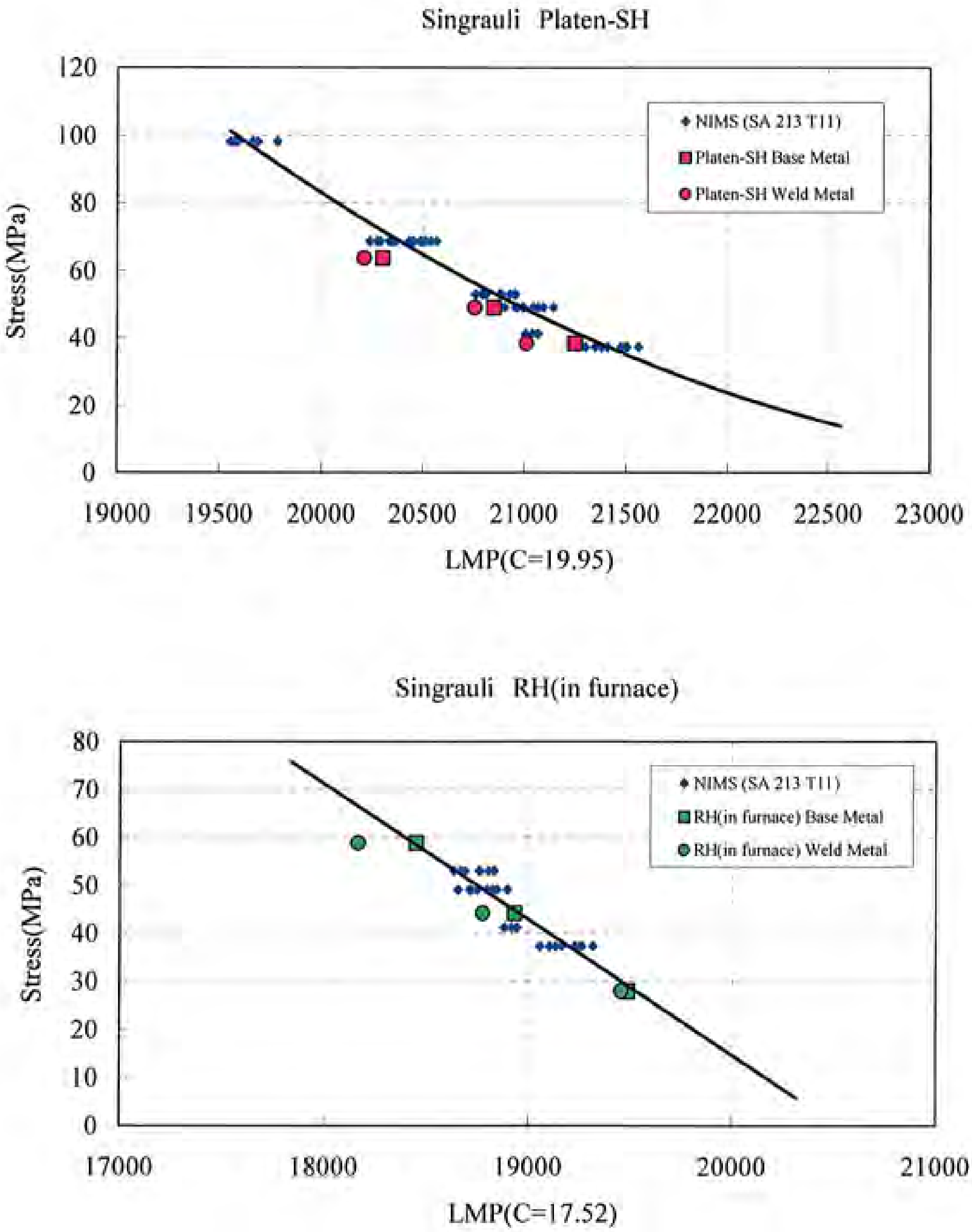


Fig I -27 The comparison of the test results with the creep rupture data of virgin materials by NIMS (National Institute for Materials science)

c. Residual life evaluation results

Residual life evaluation results of creep rupture test by parameter –method are shown in Table I -38.

The stress condition for the evaluation was calculated as the hoop stress with the measured OD, thickness of the test sample tube and the designed pressure. As for the temperature condition for the evaluation, two conditions were used for evaluation, those are the case of evaluation at the designed temperature and the other one at equivalent temperature estimated by comparison with the average creep rupture data of NIMS.

(Platen-SH tube)

The evaluated residual life (half of residual life evaluated by creep rupture test) of Platen-SH tube was 750,000 hours for base metal, 380,000 hours for weld joint portion at designed temperature 540℃of Platen-SH outlet header.

In case of evaluation at equivalent temperature 553℃, the evaluated residual life of Platen-SH tube was 290,000 hours for base metal, 150,000 hours for weld joint portion.

(RH tube in furnace)

The evaluated residual life (half of residual life evaluated by creep rupture test) of RH tube in furnace was 1,300,000 hours for base metal, 1,200,000 hours for weld joint portion at designed temperature 540℃ of RH outlet header.

In case of evaluation at equivalent temperature 551℃, the evaluated residual life of RH tube in furnace was 670,000 hours for base metal, 610,000 hours for weld joint portion.

Each portion has enough evaluated residual life at present, with the min. evaluated residual life of 150,000 hours for weld joint portion of Platen-SH tube.

Table I -38 Residual life evaluation results of creep rupture test by parameter –method

Parameter method (evaluated at designed temp.)								
Component		Material	Operation hours (h)	Hoop Stress (MPa)	Designed temp. (℃)	Residual life (h)	Creep life consumption ratio	Evaluated residual life (h)
Platen-SH	Base Metal	SA 213 T11	172,000	38.3	540(※1)	1,505,000	0.10	750,000
	Weld Metal	SA 213 T11	172,000	38.3	540(※1)	770,000	0.18	380,000
RH(in furnace)	Base Metal	SA 213 T11	172,000	27.9	540(※2)	2,783,000	0.06	1,300,000
	Weld Metal	SA 213 T11	172,000	27.9	540(※2)	2,549,000	0.06	1,200,000

Parameter method (evaluated at equivalent temp.)								
Component		Material	Operation hours (h)	Hoop Stress (MPa)	Equivalent temperature (℃)	Residual life (h)	Creep life consumption ratio	Evaluated residual life (h)
Platen-SH	Base Metal	SA 213 T11	172,000	38.3	553	598,000	0.22	290,000
	Weld Metal	SA 213 T11	172,000	38.3	553(※3)	309,000	0.36	150,000
RH(in furnace)	Base Metal	SA 213 T11	172,000	27.9	551	1,347,000	0.11	670,000
	Weld Metal	SA 213 T11	172,000	27.9	551(※3)	1,235,000	0.12	610,000

※1; Designed temp. at Platen-SH Outlet Header
※2; Designed temp. at RH Outlet Header
※3; Equivalent temperature evaluated at base metal

(7) Residual life assessment by microstructural comparison method

a. Platen-SH tube

(Microstructure observation)

The results of microstructure observation are shown in Photo I -26～30.

The summary of observation results is shown in Table I -39.

- Precipitates at gain boundary were observed in base metal, intercritical zone, fine grain HAZ and weld metal.

(Grain boundary precipitates observation)

The results of grain boundary precipitates by SEM observation are shown in Photo I -31～32.

- Precipitates at gain boundary were observed in base metal and fine grain HAZ.

(Precipitates distribution observation of extracted replica)

The results of precipitates distribution observation by TEM observation are shown in Photo I -33～36.

The summary of observation results is shown in Table I -40.

- Fine needlelike precipitates had disappeared in base metal , fine grain HAZ, coarse grain HAZ and weld metal.
- Rod-shaped precipitates and attenuated plate-shaped precipitates were observed in fine grain HAZ.

b. RH tube (in penthouse)

(Microstructure observation)

The results of microstructure observation are shown in Photo I -37～41.

The summary of observation results is shown in Table I -39.

- Precipitates free zone along grain boundary was observed in base metal, intercritical zone and fine grain HAZ.
- Granular precipitates in grain were observed in each region..

(Grain boundary precipitates observation)

The results of grain boundary precipitates by SEM observation are shown in Photo I -42～43.

- Precipitates at gain boundary were observed in base metal and fine grain HAZ.

(Precipitates distribution observation of extracted replica)

The results of precipitates distribution observation by TEM observation are shown in Photo I -44～47.

The summary of observation results is shown in Table I -40.

- Precipitates free zone along grain boundary, rod-shaped precipitates and disintegration of pearlite structure were observed in base metal.
- Fine needlelike precipitates had disappeared in fine grain HAZ, coarse grain HAZ and weld metal.

c. RH tube (in furnace)

(Microstructure observation)

The results of microstructure observation are shown in Photo I -48～52.

The summary of observation results is shown in Table I -39.

- Precipitates at gain boundary were observed in base metal and fine grain HAZ.
- Granular precipitates in grain were observed in each region.
- Granular precipitates in grain were observed in each region.

(Grain boundary precipitates observation)

The results of grain boundary precipitates by SEM observation are shown in Photo I -53～54.

- Precipitates at gain boundary were observed in base metal and fine grain HAZ.

(Precipitates distribution observation of extracted replica)

The results of precipitates distribution observation by TEM observation are shown in Photo I -55～58.

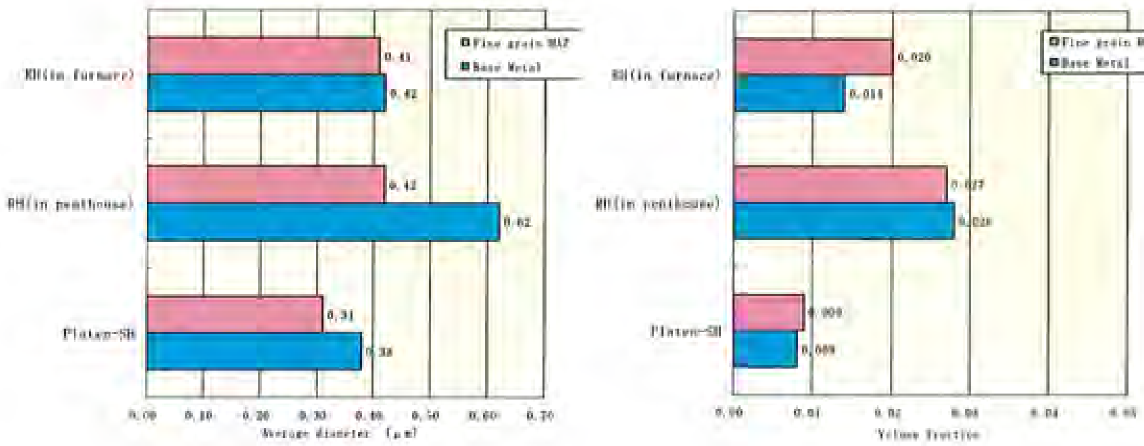
The summary of observation results is shown in Table I -40.

- Precipitates free zone along grain boundary was observed in base metal.
- Disintegration of pearlite like structure was observed in fine grain HAZ.
- Attenuated plate-shaped precipitates were observed in coarse grain HAZ.

d. Quantitative evaluation of grain boundary precipitates

The results of quantitative evaluation of grain boundary precipitates are shown in Table I -41.

- The max. value of average diameter of grain boundary precipitates was 0.62 μ m in base metal at RH tube(in penthouse), 0.42 μ m in fine grain HAZ at RH tube(in penthouse).
- The max. value of volume fraction of grain boundary precipitates was 0.028 in base metal at RH tube(in penthouse), 0.027 in fine grain HAZ at RH tube(in penthouse).



Quantitative evaluation of grain boundary precipitates〔extracted Table I -41〕

e. Quantitative evaluation of precipitates free band width along grain boundary

The results of quantitative evaluation of precipitates free band width along grain boundary are shown in Table I -42.

- The quantitative evaluation was focused on base metal of SA 213 T22 for RH tube (in penthouse).
- The precipitates free band width along grain boundary was 1.15 μ m.

f. Operational condition of residual life evaluation portion

Operational condition of evaluated components are shown in Table I -43.

The evaluation stress σ was the hoop stress calculated with designed pressure, designed diameter D and thickness t of each component.

$$\sigma = P(D-t) / 2t$$

where P : Designed pressure.

Table I -43 Operational condition of evaluated components

Component	Material	Operational condition				
		OD※1	t※1	Designed		Hoop Stress
				Temperature※2	Pressure	
		mm	mm	℃	MPa	MPa
Platen-SH	SA213T11	48.5	9.0	540	17.5	38.3
RH(in penthouse)	SA213T22	53.0	5.4	540	5.3	23.2
RH(in furnace)	SA213T11	53.9	5.1	540	5.3	25.2

※1 : Measured value

※2 : Designed temperature at Outlet Header

g. Residual life evaluation results by microstructure comparison method

Evaluation figures of residual life assessment for each components by microstructural comparison method are shown in Fig. I -28～30 and evaluation results are shown in Table I -44.

The highest creep life consumption ratio was evaluated at RH tube (in furnace) with 51% and evaluated residual creep life (half of residual life evaluated microstructure comparison method) was 82,000 hours.

Table I -44　Residual life evaluation results

Component	Material	Region	Residual life evaluation results		
			Creep life consumption ratio(%)	Residual life(Hr)	Evaluated residual life (Hr)
Platen-SH	SA213T11	Base Metal	1 ～ 2	8,428,000 ～ 17,028,000	1,300,000
		Fine grain HAZ	3 ～ 6	2,695,000 ～ 5,561,000	
		Coarse grain HAZ	0 ～ 1	17,028,000 <	
RH(in penthouse)	SA213T22	Base Metal	11 ～ 14	1,057,000 ～ 1,392,000	520,000
		Fine grain HAZ	9	1,739,000	
		Coarse grain HAZ	4 ～ 6	2,695,000 ～ 4,128,000	
RH(in furnace)	SA213T11	Base Metal	1 ～ 2	8,428,000 ～ 17,028,000	82,000
		Fine grain HAZ	3 ～ 4	4,128,000 ～ 5,561,000	
		Coarse grain HAZ	6 ～ 51	165,000 ～ 2,695,000	

Table I -39 Microstructure observation resuluts

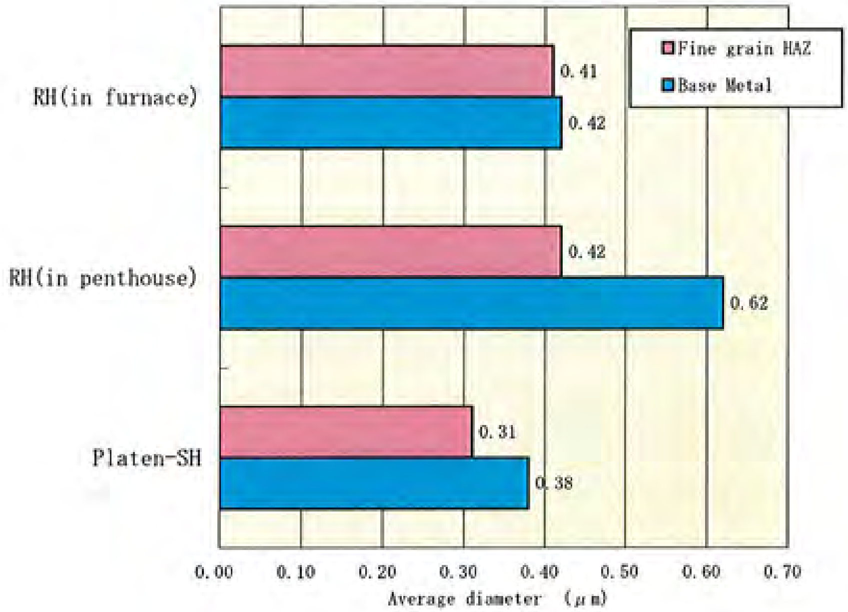
Components	Location		Observed area	OM (Optical microscope observation) Microstructural features: Precipitation at gain boundary	Precipitates free zone along grain boundary	Precipitation in ferite grain: Granular precipitates	Precipitation in ferite grain: Rod-shaped precipitates	Pearlite structure	Subgrain boundary	Ferrite grain
Platen SH tube	#12-3 (SA 213 T11)	Circumferential weld	Base metal	Appeared	Not appeared	Appeared	Not appeared	Normal		
			Intercritical zone	Appeared		Appeared	Not appeared	Normal	Normal	
			Fine grain HAZ	Appeared		Appeared	Not appeared			
			Coarse grain HAZ	Not appeared		Not appeared				
			Weld metal	Appeared		Appeared				Appeared
Reheater tube	#3-1 from leftside in penthouse (SA 213 T22)	Circumferential weld	Base metal	Appeared	Appeared	Appeared	Not appeared	Disintegrated		
			Intercritical zone	Appeared		Appeared	Appeared			
			Fine grain HAZ	Appeared		Appeared	Appeared			
			Coarse grain HAZ	Not appeared		Appeared				
			Weld metal	Not appeared		Appeared				
	#14-5 from rearside in furnace (SA 213 T11)	Circumferential weld	Base metal	Appeared	Not appeared	Appeared	Not appeared	Normal		
			Intercritical zone	Not appeared		Appeared	Not appeared	Normal	Normal	
			Fine grain HAZ	Appeared		Appeared	Not appeared			
			Coarse grain HAZ	Not appeared		Appeared				
			Weld metal	Not appeared		Appeared				Appeared
View nos. for each area				×500 (2 views) ×1000 (4 views)						

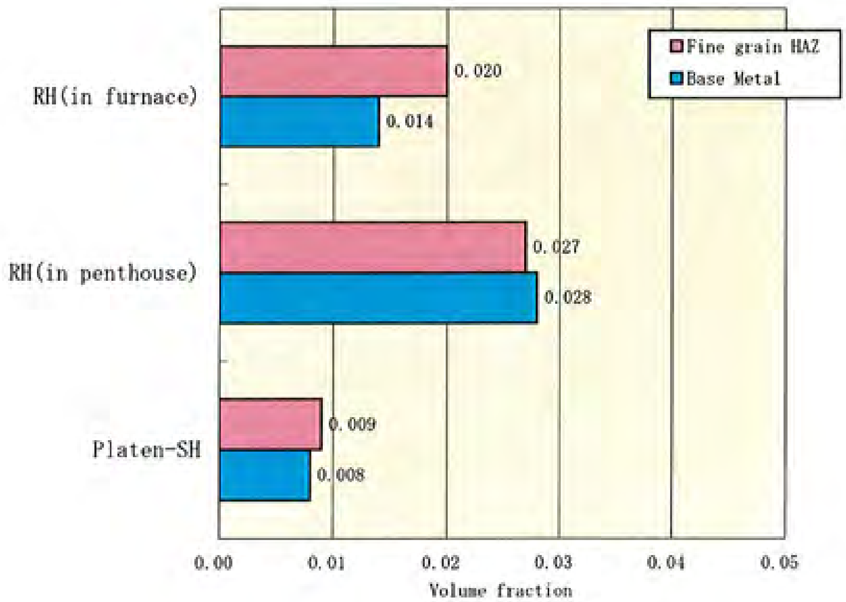
Table I -40 Precipitates distribution observation results

Components	Location		Observed area	TEM (Transmission Electron Microscope observation)					
				Precipitates features					
				Precipitates free zone along grain boundary	Precipitation in ferite grain			Pearlite structure	Aggromerated precipitates structure
					Fine needlelike and granular	Rod-shaped precipitates	Atenuated plate-shaped precipitates		
Platen SH tube	#12-3 (SA 213 T11)	Circumferential weld	Base metal	Not appeared	Disappeared	Not appeared	Not appeared	Disintegrated	
			Fine grain HAZ		Disappeared	Appeared	Appeared	Normal	
			Coarse grain HAZ		Disappeared	Not appeared	Not appeared		Normal
			Weld metal		Disappeared				
Reheater tube	#3-1 from leftside in penthouse (SA 213 T22)	Circumferential weld	Base metal	Appeared	Remaining	Appeared	Not appeared	Remarkably disintegrated	
			Fine grain HAZ		Disappeared		Not appeared		
			Coarse grain HAZ		Disappeared		Disappeared		
			Weld metal		Disappeared				
	#14-5 from rearside in furnace (SA 213 T11)	Circumferential weld	Base metal	Appeared	Remaining	Not appeared	Not appeared	Normal	
			Fine grain HAZ		Remaining	Not appeared	Not appeared	Disintegrated	
			Coarse grain HAZ		Remaining	Not appeared	Appeared		Disintegrated
			Weld metal		Remaining				
View nos. for each area				×2000 (2 views) ×1000 (4 views)					

Table I -41 Quantitative evaluation of grain boundary precipitates

Component	Material	Average diameter (μm)		Volume fraction	
		Base Metal	Fine grain HAZ	Base Metal	Fine grain HAZ
Platen-SH	SA213T11	0.38	0.31	0.008	0.009
RH(in penthouse)	SA213T22	0.62	0.42	0.028	0.027
RH(in furnace)	SA213T11	0.42	0.41	0.014	0.020



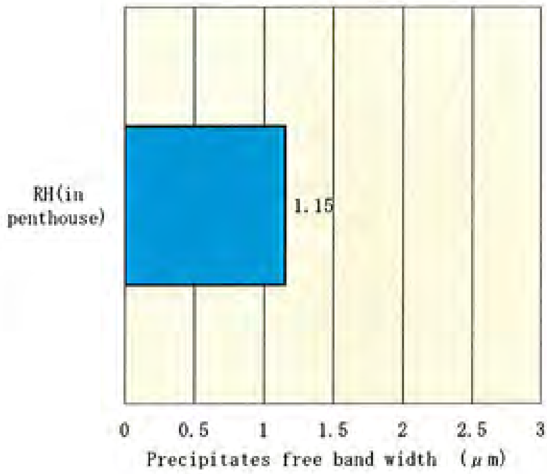


230

Table Ⅰ-42 Precipitates free band width along grain boundary

Sample tube	Material	Precipitates free band width (μm) ※1
		Base Metal
RH(in penthouse)	SA213T22	1.15

※1 : Average value of 10 measured points



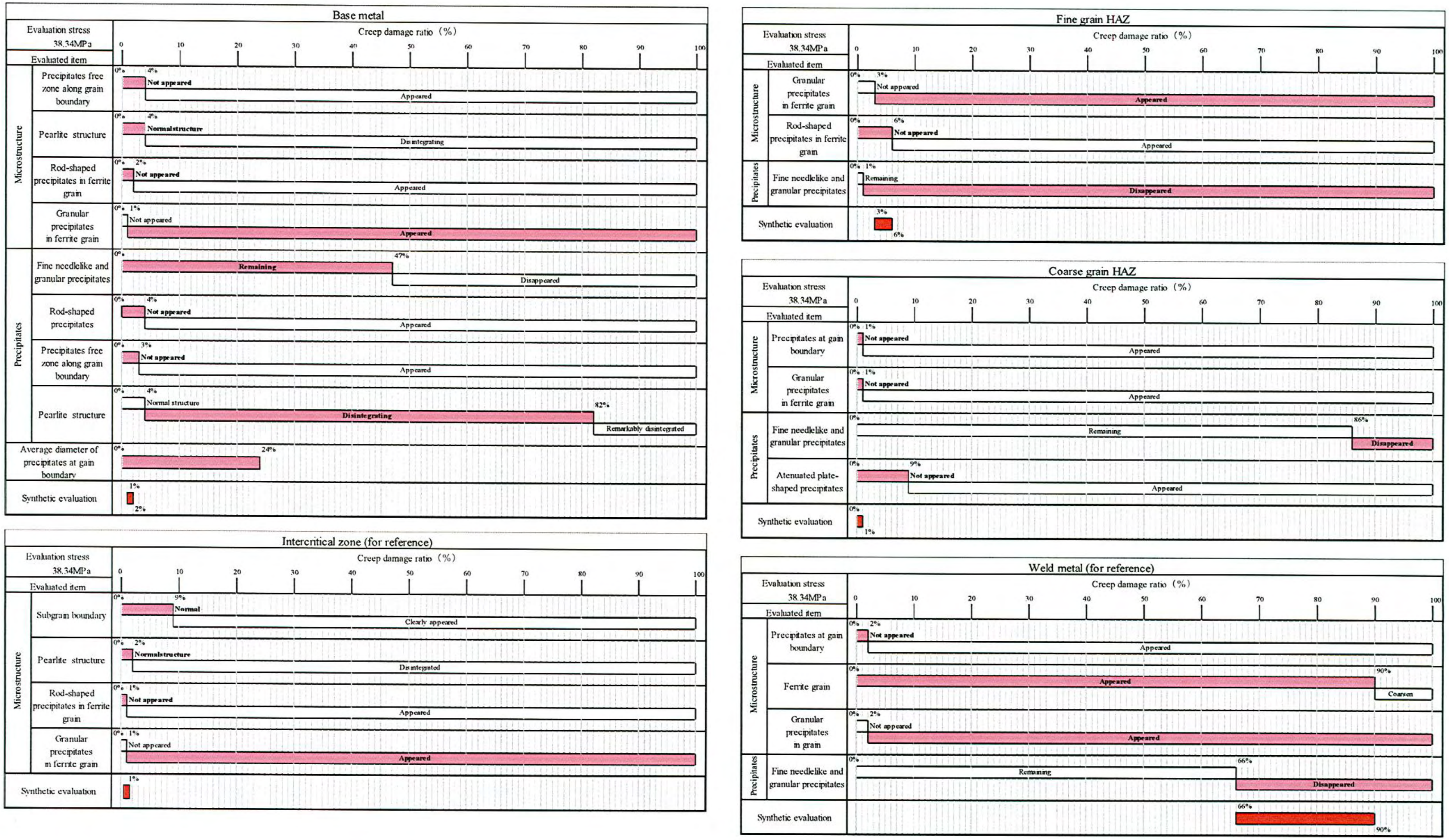


Fig I-28 Evaluation Results Platen SH